

Copyright

by

Beomrak Lee

2016

The Thesis Committee for Beomrak Lee
Certifies that this is the approved version of the following thesis:

Analysis of Oil Spill Strategies in the Canadian Beaufort Sea

APPROVED BY
SUPERVISING COMMITTEE:

Supervisor:

William L. Fisher

Krishan A. Malik

Kenneth H. Dunton

Analysis of Oil Spill Strategies in the Canadian Beaufort Sea

by

Beomrak Lee, B.S.E.

Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Energy and Earth Resources

The University of Texas at Austin

May 2016

Abstract

Analysis of Oil Spill Strategies in the Canadian Beaufort Sea

Beomrak Lee, M.S.E.E.R.

The University of Texas at Austin, 2016

Supervisor: William L. Fisher

The objective of this study is to apply historical data on ice concentration, temperature, sea level, salinity and wind speed to an evaluation of the effectiveness of oil spill responses in various seasons and regions. Keeping operations safe on ice is critical to Arctic exploration and production. Specialized construction techniques and engineering designs are required for the harsh environment in the Arctic. Factors that trigger marine oil spills include accidents involving oil transportation vessels carrying large quantities of fuel oil, releases from on-land storage tanks or pipelines that travel to water, acute or slow releases from subsea pipelines and hydrocarbon well blowouts during subsea exploration or production. In addition, dynamic ice cover, low temperatures, reduced visibility or darkness, high winds and extreme storms increase the probability of a marine oil spill. The Arctic remains among the harshest, coldest and most remote places elevating both the risk of spills and their potential impact. In order to identify effective oil spill strategies, a careful assessment of the benefits, limitations and tradeoffs related to available response techniques must be made. The findings presented here will help stakeholders select appropriate response strategies in the Arctic.

Table of Contents

List of Tables	vii
List of Figures	viii
1. INTRODUCTION	1
2. THE SIGNIFICANCE OF THE ARCTIC AREA	3
2.1 History of Oil and Gas Development	3
2.2 Technical Achievement and Innovations in the Arctic	8
2.3 Oil and Gas Reserves in the Region	16
3. TECHNOLOGIES FOR ARCTIC EXPLORATION AND PRODUCTION	20
3.1 Seismic Data Acquisition	21
3.2 Technologies for Exploration Drilling Platforms	24
3.2.1 Bottom founded Drilling Structures	25
3.2.2 Floating Structures	26
3.3 Transportation	27
3.3.1 Pipeline Transportation	27
3.3.2 Tankers	33
3.4 Ice Management	35
4. ANALYSIS OF SPIILL PREVENTION AND RESPONSE IN ARCTIC REGION	40
4.1 Oil Spill Prevention Methods	40
4.1.1 Subsurface Information for E&P Facility Design	41
4.1.2 Subsurface Well Structure	41
4.1.3 Drilling Well Muds and Cementing	43
4.1.4 Bop and Control Equipment	45
4.1.5 Subsurface Emergency Devices	47
4.2 Characteristic of Spilled Oil in Ice	48
4.2.1 Oil Spreading	48
4.2.2 Oil Movement	49
4.3 Oil Spill Response	50
4.3.1 Oil Spill Monitoring and Detection	50
4.3.2 Mechanical Recovery	52

4.3.3 In situ Burning	55
4.3.4 Dispersant	59
5. OIL SPILL RESPONSE IN THE CANADIAN BEAUFORT SEA	65
5.1 Temperature	65
5.2 Ice Concentration.....	67
5.3 Other Environmental Factors.....	71
5.4 Oil Spill Response in Open Water Season.....	73
5.5 Oil Spill Response in Ice covered Water Season.....	73
6. CONCLUSION	76
REFERENCES	77

List of Tables

Table 1: License ownership in Greenland (Government of Greenland, 2014).....	3
Table 2: Global Arctic Resource Potential (Gautier et al, 2011).....	39
Table 3: GBS exploration platform Type (Gautier et al, 2014).....	44
Table 4: Floating Structure Operation (Gautier et al, 2014)	46
Table 5: Oil spreading test results regarding existence of ice (SL Ross et al, 2010)	47
Table 6: Applicability of sensor technologies for oil spills (Dickins et al., 2010)	51
Table 7: Generic characteristic of skimmer systems (ITOPF, 2012)	54
Table 8: General In-situ burning factors for successful oil response	54
Table 9: Calculated rates of emission for an in-situ burning (Buist, 2004).....	57
Table 10: Comparison of aquatic toxicity of household cleaners to dispersants (Fingas et al, 2005)	61

List of Figures

Figure 1: Canada’s Arctic Offshore (Canadian National Energy Board, 2014).....	4
Figure 2: The Russian Arctic Seas (EIA, 2014)	7
Figure 3: Norwegian Petroleum Directorate (NPD, 2014).....	8
Figure 4: Typical Sandbag Retained Island Schematic (Chevron, 2014).....	13
Figure 5: Kulluk and Hibernia Platform (Shell and ExxonMobil, 2013).....	15
Figure 6: Trans Alaska pipeline Zigzag Design (Alaska Pipeline Service Company, 2014).....	19
Figure 7: Improved Drilling Technology to reduce surface Footprint (ConocoPhillips, 2014)	22
Figure 8: Chronology of Global Arctic Oil and Gas Milestones (Arctic Potential, 2015)...	23
Figure 9: Global onshore and offshore arctic conventional resources (Arctic Potential, 2015)	24
Figure 10: Relative Costs and Acquisition Times for Seismic Data Acquisition (ION, 2014)	26
Figure 11: Dynamics associated with managing ice (Rice et al, 2013).....	28
Figure 12: PTSM image of New England SPAN data before/after noise attenuation (Rice et al, 2013)	30
Figure 13: Arctic Exploration Drilling Systems (BP, 2014)	37
Figure 14: Histogram showing the bathymetry distribution of Beaufort extreme scours (Carr et al, 2011)	38
Figure 15: Sub-bottom profiler data within a depth 21~22m (Carr et al, 2011).....	43
Figure 16: Sequence of laying, trenching and upheaval (Palmer et al, 1990)	45
Figure 17: Arctic Leak Detection System (Thodi et al , 2012)	48
Figure 18: Transportation System Schematic (Iyerusalskiy et al, 2007).....	49
Figure 19: Ice Management Strategy and Flow Diagram (Petroleum Research, 2014).....	50
Figure 20: Average tow loads in different phases (Eik et al, 2009)	52
Figure 21: Flow Diagram of Dynamic Positioning (Samad et al, 2011).....	53
Figure 22: Offshore E&P oil spill response system and technologies (Arctic Potential, 2015)	60
Figure 23: Subsurface drill well-Completion/Production stage	52
Figure 24: Cementing (Chief council’s report , 2011)	64
Figure 25: Typical subsea BOP stack (Chief counsel’s report, 2011).....	65
Figure 26: Riser and mud/gas separator (Moyer et al, 2012)	66
Figure 27: Capping stack and shut in device (Moyer et al, 2012).....	67
Figure 28: Typical arctic oil holding capacity (Potter et al, 2012).....	64
Figure 29: Typical arctic oil holding capacity (Allen, 2012)	65
Figure 30: Throughput efficiency vs. tow speed (Mandler, 2002)	66
Figure 31: In-situ burning efficiency regarding ice concentration (Buist et al., 1981)	67
Figure 32: Response system efficiencies vs. wind speed and wave height (Allen, 2009)....	52
Figure 33: Result of 18 years of monitoring impacts to mangroves (Ward et al., 2003)	64
Figure 34: Dispersant effectiveness versus oil viscosity (Clark et al., 2009).....	65
Figure 35: Water content vs. ice concentration (SINTEF, 2010)	66
Figure 36: Dispersant effectiveness regarding salinity (SL ROSS, 2010)	67
Figure 37: Catch rates of juvenile fishes (Fodrie and Heck, 2011).....	64

Figure 38: Mean daily air temperature at Tuktoyaktuk (Timco and Frederking, 2013).....	65
Figure 39: Yearly temperature Data from 1922 to 2016 (NOAA)	66
Figure 40: Number of daylight hours as a function of latitude (Burns, 1973)	67
Figure 41: Three types of ice characterization in Beaufort Sea (Kovacs and Mellor, 1974) 67	
Figure 42: Progress of the landfast ice from 1977 to 1980 (Spedding, 1978).....	67
Figure 43: Ice thickness in the Beaufort Sea (Devon, 2004).....	67
Figure 44: Sea ice concentration in the Beaufort Sea for selected years (Modified CIS data)	67
Figure 45: Typical Ice concentration and open water period in Beaufort Sea (Modified from CIS data)	67
Figure 46: Bathymetric Data of the Beaufort Sea (NOAA)	67
Figure 47: Salinity comparison regarding the distance from shoreline (Hopky et al., 1988)	67
Figure 48: Average wind speed in the Beaufort Sea (Wilcox et al., 2007)	67

1. INTRODUCTION

Since the discovery of oil in 1920 at Norman wells in the Arctic by Imperial Oil, thousands of hydrocarbon exploration activities have been conducted. Initial offshore exploration took place primarily in the United States and Canadian territories. Large quantities of oil and gas have since been produced. Potential hydrocarbon resources in the Arctic remain significant. The Arctic region covers 6% of the world's surface area consisting of 60% ocean and 40% land (Hayes et al, 2013). During the last five decades, almost 10% of the world's conventional hydrocarbon resource have been discovered (Gautier et al, 2008). According to the United States Geological Survey, the Arctic is the "largest unexplored prospective area for petroleum remaining on earth" and holds approximately 25% of remaining undiscovered conventional oil resources (USGS, 2012). The oil and gas industry has been very active in the Arctic and has developed experience in exploration and production. From the first offshore platform operation in Cook Inlet by Shell to the more recent development of Sakhalin-2 GBS, advanced technologies have played a critical role in addressing the numerous challenges in this remote region. Safe operations are a key concern in exploration and production, and the Arctic presents a unique set of challenges due to dynamic ice cover, low temperatures, reduced visibility or darkness, high winds and extreme storms. Marine oil spills may result from accidents involving oil transportation vessels carrying large quantities of fuel oil, releases from on-land storage tanks or pipelines that travel to water, acute or slow releases from subsea pipelines, well blowouts during subsea exploration or production. Due to the remoteness of the Arctic, the impact of oil spills could be especially great.

In light of these questions, this paper aims to analyze oil spill strategies in the Canadian Beaufort Sea. To gain a better understanding of the arctic regions, chapter two

reviews historical hydrocarbon developments and reserves along with technical innovation in the Arctic. Chapter three considers specific technologies for arctic exploration and production from upstream to downstream activities and ice management. Chapter four analyzes oil spill prevention and response in the region. Chapter five evaluates oil spill strategies with respect to several factors, including ice concentration in the Canadian Beaufort Sea. Finally, chapter six summarizes and draws conclusions concerning appropriate oil spill response in the Canadian Beaufort Sea.

2.THE SIGNIFICANE OF THE ARCTIC AREA

2.1 History of Oil and Gas Development

While recent exploratory drilling activities by major hydrocarbon companies have brought global attention to petroleum development in the Arctic, oil was discovered centuries ago in this remote area. In the late 1800s, oil seeping was discovered by a Canadian explorer and in the 1920s, a Canadian based oil company started early exploration activities and discovered significant oil reserves. Following this discovery, interest and activity in the region boomed. In the U.S Arctic, two American oil companies (ARCO, Standard Oil) found oil in the Prudhoe Bay field, currently the largest oil field in North America. After the construction of the Trans-Alaska Pipeline System (TAPS) in the 1970s, companies were able to start production in the Prudhoe Bay. Gradually, international oil companies including Shell and BP tapped the oil field in the Arctic area. In spite of the commercial oil findings, extraction of petroleum has stopped due to extremely high production costs and environmental concerns (Wilson Center, 2014). In Canada, exploration activities expanded from the Northwest Territories to the Mackenzie Delta and the Canadian Beaufort Sea in the 1970s and 1980s. During this period, a cooperation of Canadian authority and national oil corporations made several oil findings (Petroleum Economist, 2014). In 2010, a Canadian led consortium including IOCs conducted drilling activities in the Canadian Beaufort Sea that would become the most distant northern wells ever drilled, located at a water depth of 1500 meters (Ebinger et al., 2014). Yet, extremely severe weather conditions and the remoteness of the location hindered early production from this region with the exception of the Hibernia field offshore Newfoundland which is Canada's largest oil and gas field from the past decade. Offshore hydrocarbon resources Canadian Arctic are considered to have a great potential. However, environmental issues combined with high capital costs and territorial disputes with

neighboring countries would slow exploration activities in the region (Henderson et al., 2014).



Figure 1: Canada's Arctic Offshore (Canadian National Energy Board, 2014)

Greenland has a more troubled oil exploration and development history. Located north of the Arctic Circle is a country mostly covered by pack ice. Seismic surveys were not carried out until exploratory drilling was done offshore West Greenland in 1971. Greenland is divided into five primary exploration blocks: one on the northeast coast, one on the south coast, and three on the west coast. West and south blocks have a long duration of ice-free season except for excessively challenging operating conditions due to old ice which is more than two years. Average environmental conditions in the territory with high-speed wind and haze vary from 10°C to - 10 °C throughout a whole year (BMP, 2004). Such extreme weather environments exacerbate the oil exploration in the east of the Greenland. In the late 70s, a group of international oil companies (Shell, ExxonMobil, BP and so on) called Kanumas conducted exploration drilling offshore West Greenland and failed to discover commercial oil field

(Casey, K., 2014). In 2000s, Shell conducted another notable drilling activity in the Qulleg-1 well with no commercial hydrocarbon discovery (Nunaoil Annual Report, 2013). After that numerous oil companies were able to access and carried out exploration activities in the area. Commercially viable discoveries have not made in this region, experts strongly remain optimistic that this area has a great potential of hydrocarbon reserves. Recently, various international oil companies play a significant role in exploring hydrocarbon fields in the territory.

Operator	Partners	Licenses		
		West Greenland	Northwest Greenland	Northeast Greenland
Cairn	Nunaoil	8	2	
Husky Oil	Nunaoil	2		
PA Resources	Nunaoil	1		
ConocoPhillips	DONG, Nunaoil		1	
Shell	Statoil, GDF Suez, Nunaoil		2	
Cairn	Statoil, Nunaoil		1	
Maersk Oil	Tullow, Nunaoil		1	
ENI	BP, DONG, Nunaoil			2
Statoil	ConocoPhillips, Nunaoil			1
Chevron	Greenland Petroleum, Statoil			2

Table 1: License ownership in Greenland (Government of Greenland, 2014)

Russia's Arctic territories are vast, accounting for more than half of the Arctic shoreline. In 1980s, significant oil fields discovered in the Barents Sea. Primary plan to achieve production in those fields was performed by a consortium between Russian contractors and Gazprom (Lunden and Fjaertoft, 2012). Shtokman, one of the biggest natural gas fields, lies in the part of Barents Sea. The field was discovered in 1998, development has been slowing due to the high construction cost and demand uncertainties. However, the future exploration activities continue to seek opportunities in the Arctic area with a support of Russian authorities. State-owned Russian gas company, Gazprom carried out first oil handling from the region and the company is actively endeavoring to tie new fields under its existing

framework at Prirazlomnoye. Despite the positive evidence of petroleum resources, oil and gas developments in the area faced postponement and cost overruns. Russia's Arctic area has remained abundant oil and gas reserves that both IOCs and state-run oil and gas companies are eager to develop.



Figure 2: The Russian Arctic Seas (EIA, 2014)

The Norway's oil segment is the country's biggest industry measured not only state income but also export profit. Hydrocarbon resources have played a significant role to finance its welfare state and enduring economic development. Thanks to the discovery of the Ekofisk field in 1969 and exploitation from the field, Norway could start its oil and gas experience. Along the way, a number of huge oil fields discovered in the North Sea which is remaining prime oil producing area. The Norwegian Arctic was the least developed of all the state's offshore territories. At present, there is only one producing hydrocarbon field in the Arctic region which is called Snøhvit field where as 60 fields in the North Sea and 16 in the Norwegian Sea are on stream (Ministry of Petroleum and Energy, 2014).

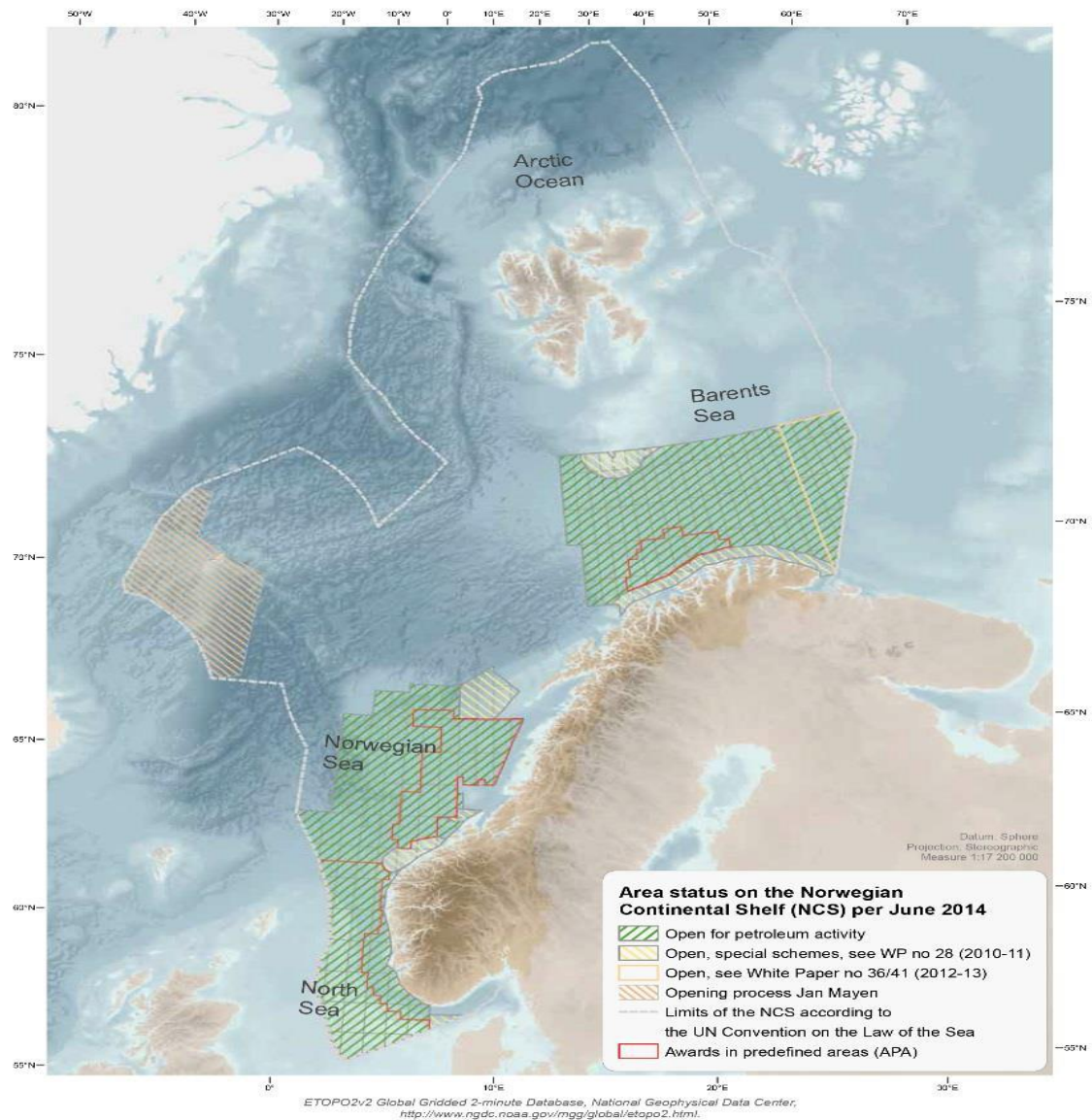


Figure 3: Area status on the Norwegian continental shelf (Norwegian Petroleum Directorate, 2014)

After oil production hit the peak in 2001, production has been decreasing dramatically. It is inevitable that new exploration and developments are required to compensate weakening output from existing fields. The Barents Sea is considered to be prospective oil and gas province to make up for the hydrocarbon production. Several fields have been found over the past few years. Until now, Snøhvit field came on stream in 2007 in the Norwegian Arctic is

the world's first offshore gas development of the Arctic region (Lunden et al, 2011). Technical and environmental difficulties delayed the project for 18 years. By 2011, considerable amount of time was spent pursuing technical feasibility. Although there were serious delays and budget overrun due to severe climatic environment and poor infrastructure, experience and expertise could ultimately be applied to new projects or in expanding current projects including Snøhvit field.

2.2 Technical Achievements and Innovations in the Arctic

Over the past five decades, Arctic exploration and development has improved remarkably. Innovation and operating experience have empowered more intricate difficulties to be overcome to cautiously evolve the global energy resources. Starting with the revelation of oil in Alaska's Cook Inlet, petroleum industry has built plans to beat a portion of the critical obstacles connected with ice loads on platforms. That experience served because the foundation for future developments that overcame different parts of the physical atmosphere, such as water depth and winter drilling in ice. From the primary major onshore Arctic-like development in North America at Norman Wells to comprehensive exploration of both onshore and offshore areas within the Canadian Arctic territories, activity in Canada has been fundamental for development of hydrocarbon offshore exploration technology. The knowledges from Canada exploratory operations from the sixties to the eighties remain clue of current largest and most challenging offshore marine projects in the Arctic area. For instance, Norman Wells discovered in the late 1800s is first oil production. Initial production in the field was irregular and periodical due to its remote location and excessively low winter climatic condition. The weather dropped as low as -51 degrees Celsius. The field has no unrestricted routes to access the closest major community of Edmonton, Alberta which is over 1,600 kilometers away.

Land base drilling was logically daring because of the remote location and extreme

climatic conditions. The larger part of hardware, including drilling rigs, supplies, and fuels was transported every year at the end of the summer. These goods were carried over the area by airplanes and trucks or other vehicles. Arctic offshore drilling demanded a significant technological step due to the extremely restricted open water season. Offshore drilling was carried out in the winter season on ice platform up to five meters thick rather than drilling in the open water season, built by spraying with high pressure pumps or flooding the current sea ice. A state of the art modular rig design permitted for transportation to boost efficiency and huge amount of capital savings. Additionally, the developed module platform rig could shortened the well construction period and save time to meet same season relief well requirements in the Arctic area.

Offshore exploration activity in the Canadian Arctic started in 1973 from artificial islands. Ice-resistant drill ships conducted deep sea drilling activities from 1976 to 1990. In spite of the harsh environment, exploratory drilling activities have been carried out successfully more than 90 offshore wells in the Canadian Arctic sea(Beaufort Sea area) (Canadian Association of Petroleum Producers, 2011). Numerous innovative drilling platforms and successfully developed operation techniques evolved into foundation for the Arctic oil exploration.

Sandbag held islands were initially utilized as a part of 1975 in shallow waters with restricted open water season also, shore-fast ice. The islands are intended to oppose ice strengths and to minimize the erosional impacts of summer tempest waves. The capacity to utilize islands all through the winter is a noteworthy point of interest over the restricted penetrating season of routine drill ships and lift stages. In this manner, finishing of the boring program and full assessment and testing of the well can be accomplished in one season. Moreover, outline wells through directional penetrating on the same island are conceivable at extraordinarily diminished expenses. The sand sack held island utilizes a berm of sandbags

to minimize the volume of fill required in regions where sand acquire is rare. It has been utilized viably as a part of generally shallow water, up to 7 m depth. The sacrificial beach island is described by long continuous shorelines and submerged slants of around 1: 15. The shorelines power storm waves to break and, along these lines, scatter their vitality before achieving the island appropriate. In winter, the shoreline decreases ice sheet which forms into a defensive rubble field around the island. Optional incline assurance is given by sandbags and channel material on the shorelines and around the boring surface (C.V. Mancini et al, 1978).



Figure 4: Typical Sandbag Retained Island Schematic (Chevron, 2014)

As the seawater deepened, artificial islands became obsolete, but the ambition to drill deeper sea grew, specially-designed drilling ships capable of operating in arctic ice conditions have been used during the summer season since 1976. The professionally equipped mooring system supported quick disconnection from the anchors in case of ice encroachment. Also, to reduce the severity of the subsea ice condition, numerous techniques including ice management operations, big bit and drilling procedures were introduced. In 1983, an axis-symmetrical drilling vessel (Kulluk) was built and started operations. This drillship could perform safely not only in open water but also in ice covered water, thus lengthening drilling season.

Long accessible open water seasons integrated with use of conventional deep water development systems that have been modified for icy conditions have allowed several fields

to be developed. Production technology systems available for cold climate and Arctic conditions have been developed from the Hibernia GBS to the White Rose and Terra Nova FPSO (Masterson et al, 1991). Hibernia Gravity Base Structure (GBS) is the first iceberg resistant offshore platform. This platform has equipped with an advanced ice management software monitoring and alarming approaching icebergs. Icebergs are diverted by the supporting barges using ropes or water guns. With 20 years of operating experience, Hibernia's ice detection and prevention technologies have been evolved effectively. 30 km away from Hibernia, Terra Nova field was found in 1984 less than 100 meters of sea depth. To deal with deeper sea, a floating production storage and offloading vessel (FPSO) was uniquely designed to withstand iceberg collision as well as quick release and ice management system.



Figure 5: Kulluk and Hibernia Platform (Shell and ExxonMobil, 2013)

The Cook Inlet area of Alaska began to be drilled in the early part of the 20th century. But the significant exploration started after 1950s due to the extreme weather and high cost by poor infrastructure. Swanson River region became Alaska's first inland oil producing field in 1957 and a couple of years later, two U.S. based oil companies (Union Oil Company, Ohio Oil Company) successfully discovered gas field in the Alaska's Cook Inlet as well. These

two major discoveries prompted broad investigation and generation on both sides of the inlet. Followed by the significant exploration activities, the biggest oil field in North America, Prudhoe Bay, was found. However, extremely remote and logistically tested environment, substantial amount of time and cost and a suitable oil export system was required for its development. Not long after the success, a joint venture was shaped to develop a 1300-kilometer onshore pipeline to the nearest ice-free harbor in Valdez. Construction hurdles coming from geological challenges mountains, rivers and seismically active Denali fault. Moreover, to prevent the permafrost from liquefying because of the hot oil stream and to guarantee the funnel did not die down, more than half of the pipeline must be hoisted. Be that as it may, the over the ground plan conceivably took into account heat exchange to the permafrost through the vertical bolster structures. In this way, a separate refrigeration framework was made and more than 124,000 thermosiphons were applied along the pipeline. To reduce the pipe stresses associated with variant temperature (ranges from 50 to 90 degrees Fahrenheit) and earthquake, a specially designed pipeline configuration (zigzag) was developed.



Figure 6: Trans Alaska pipeline Zigzag Design (Alaska Pipeline Service Company, 2014)

At the same time, Reduction of the surface footprint of the oil field development has been advanced over the past three decades. Wells that were once penetrated from 65-acre of land cushions in the 1970s are presently penetrated on much littler 13-acre of land cushions and, given the great progress in horizontal drilling systems, can get to more than ten times the subsurface territory.

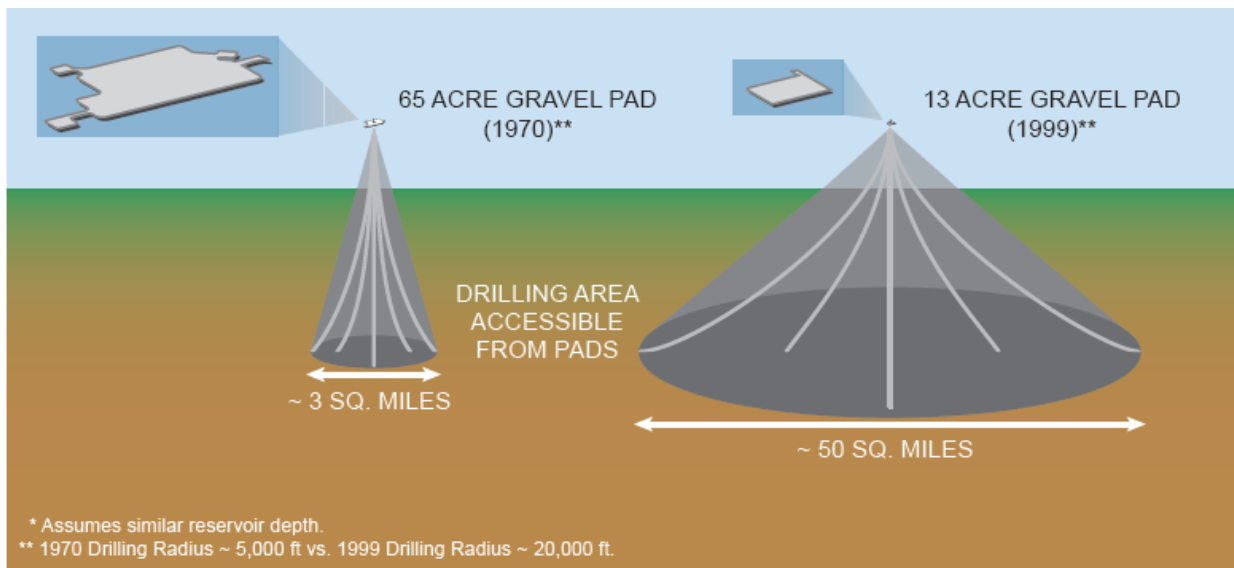


Figure 7: Improved Drilling Technology to reduce surface Footprint (ConocoPhillips, 2014)

While penetrating on ice islands was taking place in the Canadian Arctic, the first exploratory well was drilled from an ice island in the U.S. territory happened in the 1970s. With advancement of the drilling technique along with gravel and ice island technology exploration activities expanded to the deeper federal Offshore Continental Shelf (OCS). 35 well drilling activities have conducted using a cutting edge technology deep water drilling rigs including ice-resistant drill ships and platforms since 1982 (Masterson et al, 1991).

Russia has accumulated experience of ice-going ships with its massive Arctic coastline and hydrocarbon production offshore Sakhalin Island's coast made the later development of the Prirazlomnoye field and the Varandey oil export terminal which are situated in the north of the Arctic Circle and work in almost year-round ice covered conditions (Wood Mackenzie,

2014). Meaningful exploration activities happened in the late 80s in the Russian Arctic Sea. The first manned marine GBS located in the north of the Arctic Circle was constructed. Considering long period (up to 10 months) of ice coverage throughout the year with harsh temperature, this is an important achievement. The platforms in Sakhalin Island are able to operate throughout the year in ice-covered waters and inland drilling rigs have accomplished more drilling than anything that has come before and longest extended reach drilling at close to 13 km (Exxon Neftegas Limited, 2014).

Norway's long-term open water season has allowed numerous deep sea technologies including the world first subsea to shore gas project in Norway's Arctic territory. The Snøhvit field has taken commercial development of deep sea Arctic gas field into consideration of utilizing coastal LNG terminals specially constructed for severe Arctic temperatures. Norway has a long history of offshore oil and gas exploration, with more than 100 exploratory wells bored around Arctic region since exploration began in the North Sea in the mid-1960s took after by exploration activity in the Barents and Norwegian Sea in the late 1970s (NPC, 2015). Hydrocarbon exploration in Barents Sea was successful limited because of a commercially infeasible project. Recently, oil and gas exploration has risen and huge amount (174 million barrels of recoverable oil) of hydrocarbons have found from Goliat field to the Johan Castberg field and the Hoop area. However, lack of infrastructure and extremely harsh environment would hinder the commercial development.

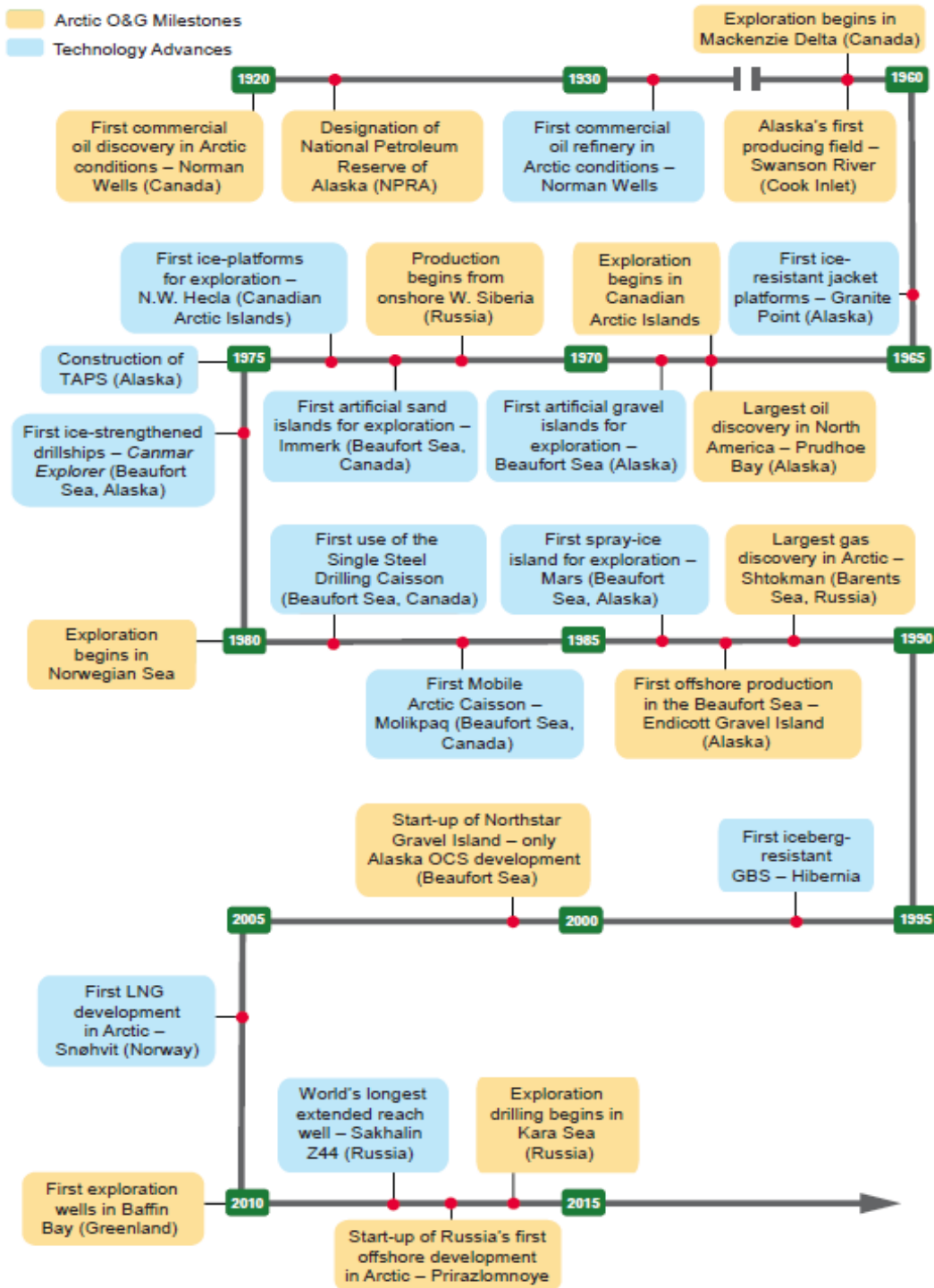


Figure 8: Chronology of Global Arctic Oil and Gas Milestones (Arctic Potential, 2015)

2.3 OIL AND GAS RESERVES IN THE REGION

More than 60% (30 billion barrels of oil, 920 TCF) of the hydrocarbon resources in the Arctic region are untapped. Since its exploration began, 23 billion barrels of crude oil and 550 Trillion Cubic Feet (TCF) of natural gas have been produced (IHS, 2014). Out of 525 Billion Barrels of Oil Equivalent (BBOE), 425 BBOE has yet to be discovered. This accounts for a quarter of the world's untapped conventional hydrocarbon resource potential. The aggregate Arctic asset potential incorporates 106 billion barrels of petroleum, 2,232 TCF of natural gas, and 47 billion barrels of Natural Gas Liquids (NGLs). Natural gas alone covers more than 70 percent of the total Arctic resource potential in oil equivalent barrels. Such a plenty of natural gas is a sign of the Arctic's capability to supply the world with sustainable energy for long haul. Still, this will require gas exporting terminals, as a rule, is a lack of infrastructure. Oil and NGLs represent 30 percent in the Arctic which is an abundant gift considering it accounts for about 20 percent of the untapped conventional oil and NGLs remaining the world (Schenk, 2012).

Resource Type		United States		Canada		Russia		Greenland		Norway		Total
		Onshore	Offshore	Onshore	Offshore	Onshore	Offshore	Onshore	Offshore	Onshore	Offshore	
Oil (BBO)	Undiscovered	9.9	21.9	1.4	11.3	12.6	17.9	0.8	15.3	0.1	4.5	96
	Discovered	1.4	0.7	0.4	1.5	4.6	0.5	0.0	0.0	0.0	0.9	10
Total Oil (BBO)		11.3	22.6	1.8	12.8	17.2	18.4	0.8	15.3	0.1	5.4	106
Natural Gas (TCF)	Undiscovered	91.3	138.8	11.9	76.5	166.2	977.8	6.2	129.9	1.2	112.2	1,712
	Discovered	99.7	28.1	12.3	11.1	183.7	177.4	0.0	0.0	0.0	7.9	520
Total Gas (TCF)		191.0	166.8	24.2	87.5	349.9	1,155.3	6.2	129.9	1.2	120.1	2,232
NGLs (BBNGL)	Undiscovered	2.4	3.4	0.2	1.3	4.4	23.1	0.4	8.8	0.0	1.0	45
	Discovered	0.0	0.7	0.0	0.0	1.0	0.5	0.0	0.0	0.0	0.1	2
Total NGLs (BBNGL)		2.4	4.1	0.2	1.3	5.4	23.6	0.4	8.8	0.0	0.0	47
Total Resource (BBOE)	Undiscovered	27.5	48.4	3.7	25.3	44.7	203.9	2.2	45.8	0.3	24.2	426
	Discovered	18.1	6.1	2.4	3.3	36.2	30.6	0.0	0.0	0.0	2.3	99
Total Resource (BBOE)		45.6	54.5	6.1	28.7	80.9	234.6	2.2	45.8	0.3	25.4	525

Table 2: Global Arctic Resource Potential (Gautier et al, 2011)

Almost 75 percent of the hydrocarbon resource potential is estimated to be located Arctic offshore. This is not astounding considering most Arctic oil and gas production to date has been inland. In addition, complexity related to Arctic offshore development has remained mostly unexplored and underdeveloped. The Arctic seaward stays one of the most encouraging region in the world for hydrocarbon resource, substantial part of which is estimated to be able to develop utilizing existing technologies including ice-resistant bottom-founded or GBSs. Approximately 40 percent of undiscovered conventional hydrocarbon resource potential are considered to be located in less than 100m water depth. Russia is assessed to have 60 percent of the hydrocarbon asset potential in the Arctic mostly from natural gas. The U.S. Arctic territory is assessed to have nearly 100 BBOE and three quarters of hydrocarbons are unexplored.

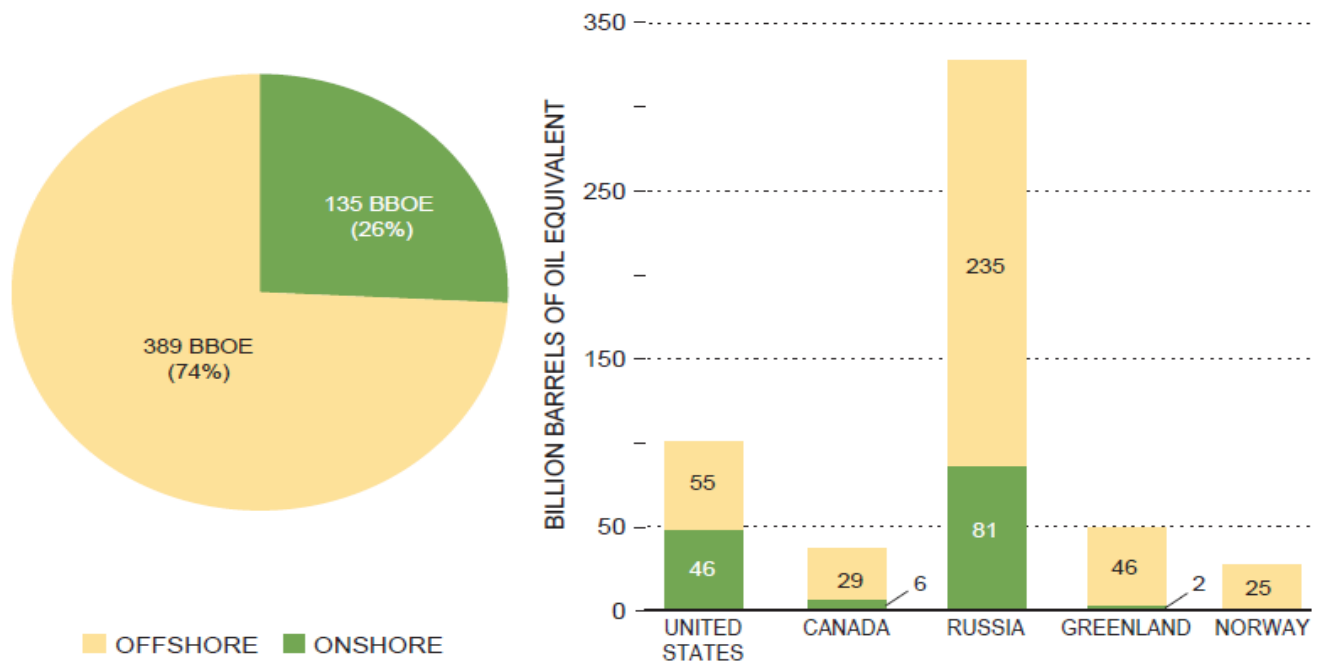


Figure 9: Global Onshore and Offshore Arctic Conventional Resources (Arctic Potential, 2015)

The U.S has yielded more than 16 BBO in the Alaskan Arctic region and 5BBO is still untapped (IHS, 2014). The U.S. has focused on development and production in the North Slope area and because of the Trans-Alaska Pipeline System, oil transportation to the consumers has been made possible. Due to the poor infrastructure, produced gas is not exported but consumed for enhanced oil recovery. Alaska's North Slope region accounts for more than half of hydrocarbon potential which is considered to be natural gas. Poor gas export infrastructure has hindered gas development in this region. The Alaskan Arctic has abundant of unconventional resource potential. One BBOE of petroleum and NGLs and 60 TCF of natural gas. Moreover, unconventional hydrocarbon resources including heavy oil and gas hydrates will grow as the exploration and production technology advances (Collett, 2008). Approximately 10 TCF of hydrocarbon resources have been discovered in the offshore Alaska. Most of undiscovered hydrocarbon resources are considered to be deposited in less than 100 meters water depth. Numerous discoveries have been made in the Chukchi and Beaufort Seas, but only one project (Northstar Field) has been commercially operated. \$3 billion dollars of lease sale participation in 2008 showed that Alaska's Arctic region has great potential profitability of oil. Alaska's sub-Arctic (south and central) area has less conventional resource potential than northern region of Alaska. Cook Inlet area with numerous producing oil fields holds oil and gas reserves more than 70 percent of this region.

Since its first oil production in 1920, Canadian Arctic has yielded more than a quarter BBO and has three quarter BBOE of hydrocarbon reserves which is mostly considered to be natural gas. Most hydrocarbon production has been made in this region. A number of exploration activities in the eastern Canadian Arctic offshore have been conducted for the past several decades, but commercial developments have not made so far. However, eastern Sub-Arctic region's active oil wells have increased production because of the oil field developments (Hibernia, Terra Nova, White Rose fields). Canada accounts for 25 percent of

Arctic hydrocarbon resource potential which is mostly natural gas. Unlike the U.S. offshore resources, most of unexplored oil deposits exist relatively deep under the ocean floor. This situation needs advanced floating or subsea technology (National Petroleum Council, 2011).

Most of the Arctic natural gas has been produced by Russia which is the largest gas producer. With huge amount of hydrocarbon resource potential offshore Russian Arctic area, Russian Arctic production has mainly been made onshore except for the world class hydrocarbon field located in the Barents Sea. Russia's long Arctic coastline reflects the largest hydrocarbon resource potential which is mostly natural gas (80% of total resource potential). Great hydrocarbon resource potential across the Russian offshore shows that Russia will play a critical role in Arctic hydrocarbon production over the next several decades.

Despite the exploration activities and promising potential hydrocarbon reserves (48 BBOE) in Greenland, no commercial quantities of oil and gas have been found. Most of hydrocarbon deposits are considered to be over a depth of 100 meters sea water. Contrary to active exploration in West Greenland in the past decades, offshore Northeast Greenland with great resource potential began exploring recently (Hansen, 2013).

Norway's pioneering Arctic development including the only LNG export terminal in Snøhvit field and exploration activities have led to great success. More than 1 TCF of natural gas production shows that almost of Norwegian total resource potential is assessed to be natural gas (approximately 80%). Extensive exploration activities is expected to take place near Barents Sea which is over a depth of 100 meters sea water and open water (Gautier, 2011).

Globally, Arctic region is estimated to have approximately 525 BBOE of hydrocarbon deposit (70% gas, 30% petroleum). To lower the uncertainty of hydrocarbon reserve in the Arctic area, considerable amount of exploring work is required including geological and environmental studies.

3. TECHNOLOGIES FOR ARCTIC EXPLORATION AND PRODUCTION

Innovation in exploration and production has enabled one of the largest and most complicated drilling and production facilities to operate safely offshore. In the past three decades, the development of very refined methods to interpret images of seabed geological structures and the advancement of drilling method have led to penetrating the sub-surface more deeply (both vertically and horizontally), thus accessing to new reserves. Offshore platforms the size of a football field are able to conduct tens of exploratory drills over a width of 16 kilometers or more. From seismic data acquisition to stable production and hydrocarbon transportation, new methods for exploration and production have planned in the Arctic region. Because the extremely harsh Arctic environment can be challenging for exploration and production, conventional methods must be changed and used in new ways.

Exploration and production procedures in the Arctic should enhance safety, environmental protection and cost effectiveness. The proper combination of technologies could affect the prudent exploration and production of this harsh environment. A key to success in the Arctic is lengthening of the drilling season without affecting ice-dependent inhabitants, so that all three of these goals can be met.

3.1 SEISMIC DATA ACQUISITION

Until 2009, 2D seismic data acquisition under sea-ice conditions was impossible. Advanced, high-quality 3D seismic and newly introduced time-lapse seismic techniques have improved geological risk assessment and oil recovery. However, various seismic acquisition approaches need to be applied differently and on the basis of the exploration and production project's lifecycle stages and resolution of the seismic data and location.

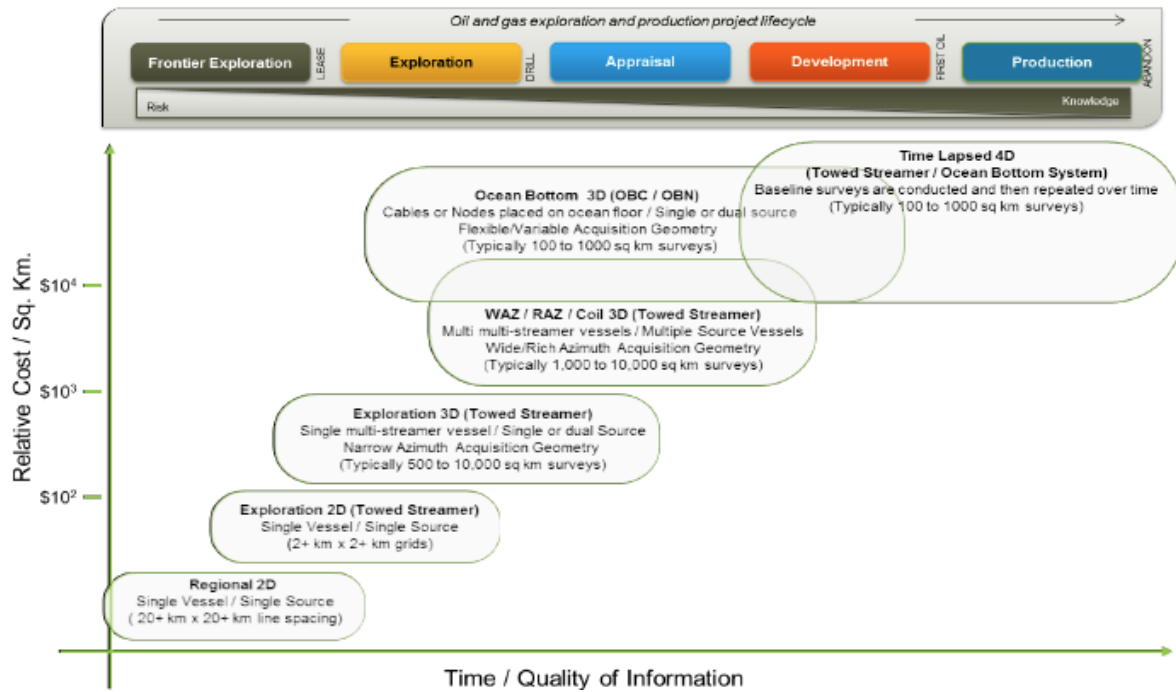


Figure 10: Relative Costs and Acquisition Times for Seismic Data Acquisition (ION, 2014)

Severe working and regional environmental issues challenge the acquisition of subsea seismic data in different Arctic locations. Darkness, intense cold, and ice-covered seawater hinder seismic data acquisition. Using conventional data acquisition equipment and vessels can be risky in these situations.

To acquire seismic data successfully, three different types of operational techniques are specified in sea ice. In “Ice free” condition, conventional seismic equipment is operated similarly to open-water use. “Ice avoidance” means that seismic data acquisition is conducted in the presence of pack ice. Seismic products and specially equipped vessels might be required to avoid sea ice contact. “Under” ice means that both conventional and non-conventional seismic apparatus and equipment are needed to carry out data acquisition (Rice et al., 2014).

Ice Free

To reduce the risk of failed data acquisition, seismic activities should be conducted in sea-ice-free situations. Major seismic data acquisition has been carried in “ice free” conditions to maximize the efficiency and lower cost of conventional seismic equipment and techniques. A large amount of seismic data has already been acquired in the Arctic offshore by running conventional seismic procedures and equipment during the open-water season. Current offshore seismic activities depend on an array of hydrophones (receivers) and air-guns (source). Exploration data acquisition plays an important role prior to well drilling because of its key role in the design of a safe well program. Designing the drilling mud and casing string for a well which is a critical factor for well control is derived from the seismic data. Therefore, the vessel type and seismic equipment such as an enhanced Global Positioning System (GPS) are chosen carefully to reduce health, safety, and environment (HSE) risks.

Ice Avoidance

Ice avoidance could be critical to carry out seismic survey in ice covered water. Without ice avoidance systems, surveys could be limited. Ice management systems with experienced crew will greatly mitigate the contact with ice during seismic data collection

Under Ice

Unlike data collection in a conventional voyage, successful seismic data acquisition in “under ice” conditions is especially challenging. Specific vessel coordination and a trained nautical crew are imperative for safe vessel operation in ice. Opening a sea trail using an ice-breaking vessel in front of the seismic ship demands prediction of drifting ice. Multi-vessel seismic activities are enabled by modern GPS associated with an ice-management system.

Installation of the ice management system in all vessels supports the ice tracking, visualization, and risk mitigation strategies used in Arctic offshore seismic exploration but with a more comprehensive understanding of sea ice.

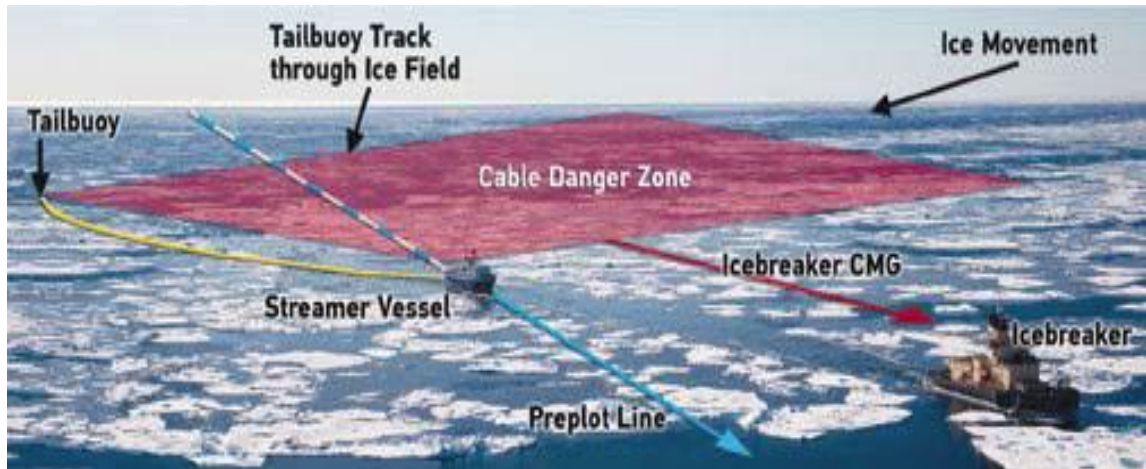


Figure 11: Dynamics associated with managing ice (Rice et al., 2013)

Given the arduous operational environment associated with ice (vessel breaking ice, diffracted ice and ice multiples) seismic data processing of the Arctic region is particularly difficult. “Under ice” seismic exploration that entails towing the seismic equipment (18 ~20m below sea level) can lower the resolution of acquired data. Noise-attenuation techniques arising from ice and glacier movement are developed to improve the image of the Arctic marine subsurface. Safe and efficient seismic data acquisition under an ice covered sea is the result of integrated operating techniques and experienced operators. Further research on collecting 3D seismic data in ice laden water will be needed to improve image resolution in this extremely harsh environment (Rice et al., 2013).

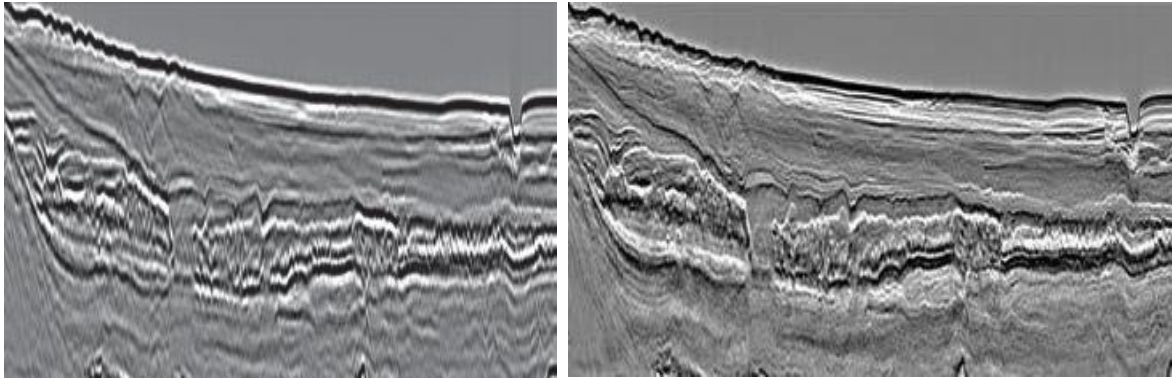


Figure 12: Pre-stack time migration image of New England SPAN data before/after noise attenuation (Rice et al., 2013)

3.2 TECHNOLOGIES FOR EXPLORATION DRILLING PLATFORMS

From the Arctic waters of Alaska to the shallow waters of the Canadian Mackenzie River, the first offshore Arctic hydrocarbon exploration started with man-made gravel islands five decades ago. These exploration platforms were required to have ice-resistant offshore design and drilling technology with ice management to reduce ice loads transferred to a moored drilling unit. As exploration activities expand to distant offshore areas, platforms including bottom-founded and floating structures have advanced. Drilling operations under Arctic drift ice can be very challenging. Both fixed and floating platforms (artificial islands, bottom-founded structures), need to be equipped with an ice-monitoring system to avoid colliding with ice and to support considerable loads of ice. In the event of interaction with large blocks of uncontrollable ice, floating platforms must detach safely from the mooring lines. The Arctic sea ice is the most technically demanding challenge of the offshore Arctic exploration. Despite the open water conditions in the offshore Arctic, pack ice is drifting on the across the Arctic sea surface, propelled by wind and by ocean waves. Ice-monitoring systems and ice breakers are key to safe Arctic exploration activities, in both open water and

ice-covered periods.

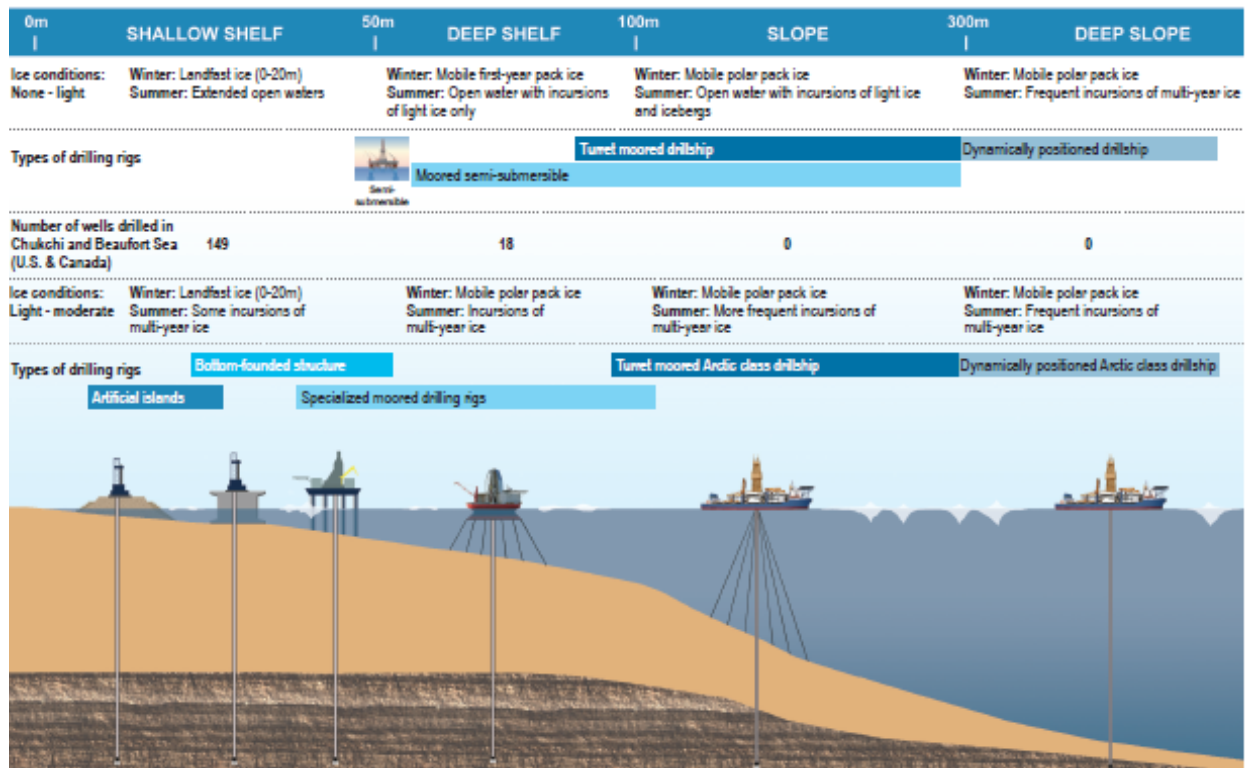


Figure 13: Arctic exploration drilling systems regarding sea level (BP, 2014)

3.2.1 Bottom-Founded Drilling Structures

Deep-water exploration prompted the advancement of various structures utilizing caisson-retained islands and bottom-founded hydrocarbon-support structures, typically called Gravity Based Structures (GBS). Man-made gravel island structures have been widely used in Arctic shallow water. In some cases, ice used as a building material was applied to reinforce drilling facilities for provisional islands. In contrast, GBS systems lie on the ocean floor and offer the advantage of imperviousness to ice and wave strengths through the base resistance from the ocean bottom. Bottom-founded structures can also be used to conduct drilling in shallow waters. To date, there are several types of GBS drilling platforms.

Type	Remark
Concrete caisson retain island	First artificial island provided an economic extension of gravel island
Steel GBS type MODU	Designed to resist collision with ice pack Advanced level of ice loads measurement
Steel caisson retained/sand-filled island	Caissons interconnected to enhance stability in case of interaction with ice
Single Steel Drilling Caisson	Improved water depth range and stability with new steel support (MAT)
Concrete Island Drilling System	Concrete/steel hybrid GBS platform

Table 3: GBS exploration platform types (Gautier et al., 2014)

Because of their high cost and absence of suitability for Arctic exploratory drilling offshore, GBS drilling platforms are unlikely to be developed unless they are used in an extensive system involving, multiple wells located in shallow waters. Given the considerable hydrocarbon potential of the Arctic shallow waters, gravity-based structures will be improved.

3.2.2 Floating Structures

Floating platforms permit drilling activities to go deeper than can man-made gravel islands and gravity-based structures. Early types of floating platforms had limited access to the Arctic offshore in winter season due to the ice interaction risk while in operation. Use of ice-breaking vessels and ice management systems in conjunction with floating platforms could boost exploratory activities offshore. In recent years, drilling activities using floating platforms have been conducted in five areas.

Location	Operator	Remarks
Chukchi Sea /Beaufort Sea	Shell	Plans to finish exploratory drilling over several drilling seasons
West Greenland	Cairn Energy	Extensive open-water season Challenges with iceberg drift
Flemish Pass New foundland	Statoil	Located in deep water(>1,000m) Successful iceberg management over the past 4 decades
Norwegian Barents Sea	Statoil	Open-sea condition influenced by the Gulf Stream
South Kara Sea	ExxonMobil	Relatively long open-sea condition

Table 4: Floating Structure Operation (Gautier et al., 2014)

Future development of floating platforms will entail comprehensive measurements of sea ice loads, use of Quick Connect Disconnect (QCDC) mooring systems and advanced global positioning systems, and deployment of advanced global positioning systems.

3.3 TRANSPORTATION

3.3.1 Pipeline Transportation

Marine pipelines might be utilized to convey hydrocarbons from the offshore production facility to an inland oil and gas refineries. Further transportation of hydrocarbons to consumers could be by ship or by onshore pipelines. Marine pipelines might also be applied to transport hydrocarbons from subsea wellheads to inland facilities. Technologies associated with subsea wellheads and production platforms are key elements for developments of the deep Arctic Ocean because they can be connected to the shoreline without the risk of building floating production platforms in ice-covered seas. In addition, subsea wellheads could be

useful for optimizing the number of production platforms in sparsely distributed hydrocarbon fields. Arctic offshore pipeline construction and operations differ from those in temperate regions.

Mitigating the contact with ice is the key element of offshore pipeline and offshore equipment design. Extensive ice masses float around and are thrust by pack ice and carried by wind and ocean currents. When the ice masses hit the ground, they tend to keep on moving and cut gouges into the seafloor. Masses of ice can be of various sizes, depending on their location and environment. For instance, ice masses are typically small because they are incapable of arriving at shallower water due to the lack of driving force to thrust them against the friction of the seafloor. Larger but fewer masses of ice reach the seafloor and cut deep gouges (> 50 m wide and 5 m deep). When the gouge occurs in the seafloor, it is likely to have piping distortion even though the ice mass did not directly impact the marine pipeline (Palmer, 2000).

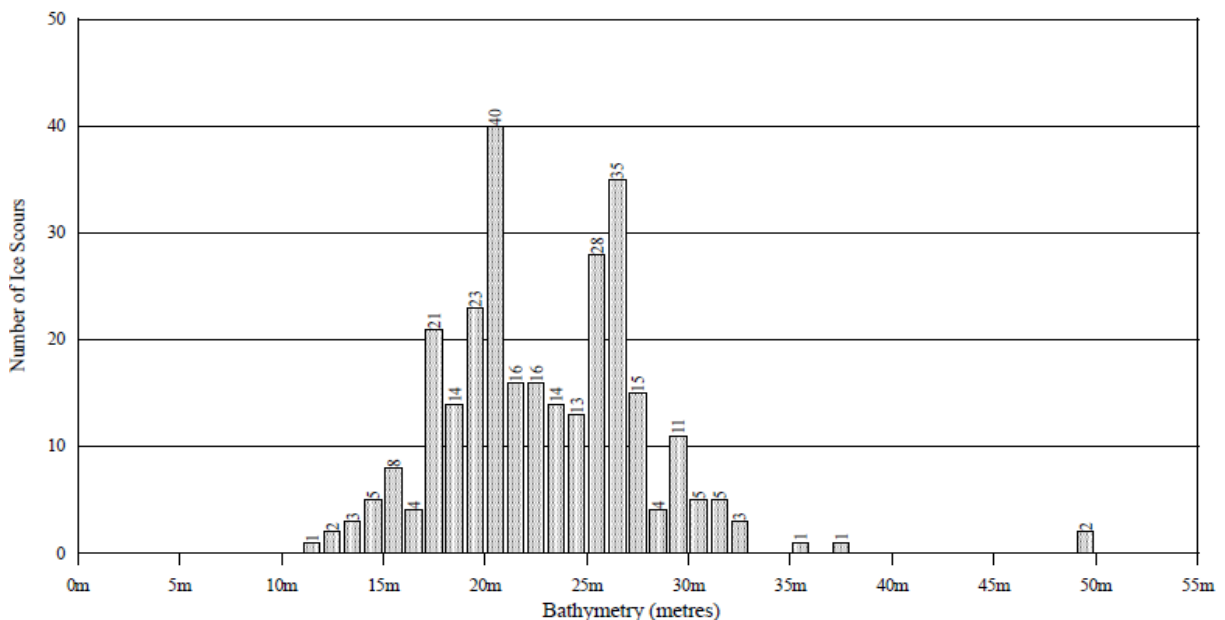


Figure 14: Histogram showing the bathymetric distribution of extreme scours in the Beaufort Sea (Carr et al., 2011)

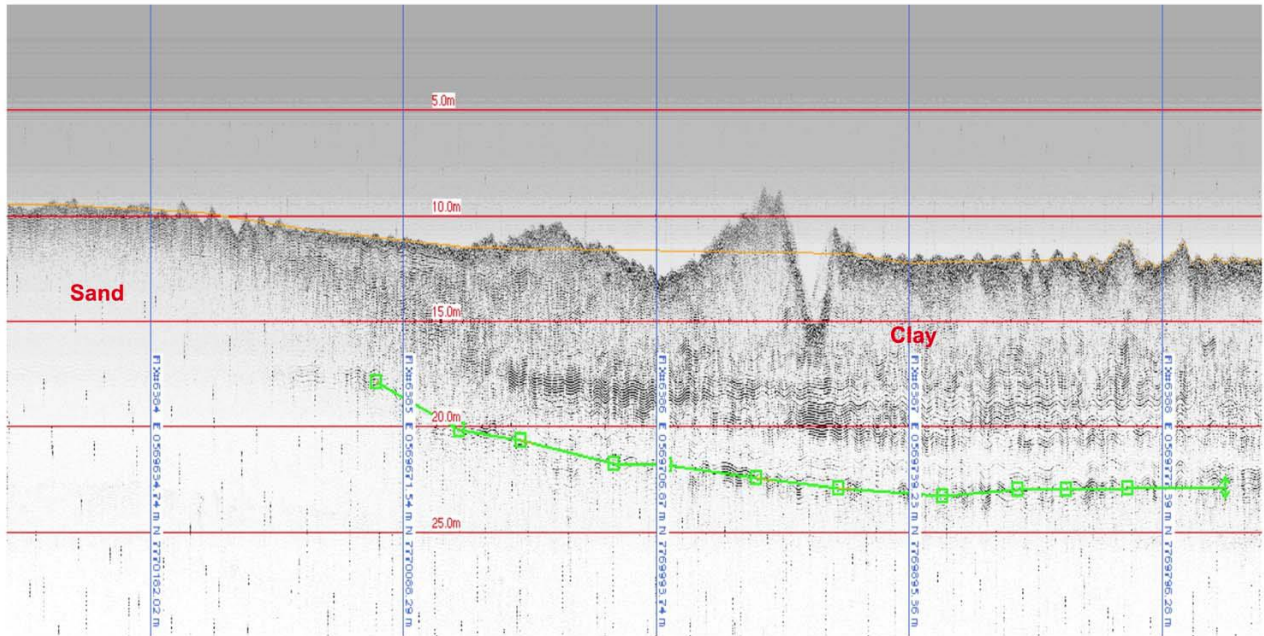


Figure 15: Sub-bottom profiler data in the Canadian Beaufort Sea (Beaufort shelf) at a depth of 21~22m. The orange line represents the unscoured seafloor and the green line represents recent marine sediment (Carr et al., 2011)

Therefore, any subsea equipment situated in depths of sea water inside the range of ice keels must be shielded from contact with the ice. Seabed pipelines are required to be laid beneath the range of gouging ice. Subsea wellheads and their associated equipment in the Arctic region also need strong protecting structures. In the Arctic, ocean ice, ranging from 1.5 to 2.2 m in thickness (covering around 90% of the ocean surface) develops during the winter. Unlike the land-fast ice edge attached to the coast, this ocean ice is able to move and is likely to be distorted. Thick floating ice hinders hydrocarbon production operations, including subsea equipment access and maintenance.

Ice cover also has a negative impact on pipeline leak detection methods based on visual inspection. When a pipeline transports hydrocarbons at a higher temperature and pressure than ambient conditions, it tends to extend. If the pipeline is not allowed to extend, the pipe will

build up axial force. If the energy applied by the pipeline on the ground surpasses the vertical restraint against moving upwards that is generated by the submerged pipeline's load, significant vertical pipe displacement (upheaval buckling) might occur (Palmer et al., 1990). Safety concerns about Arctic subsea pipeline maintenance associated with upheaval buckling are exacerbated given the Arctic's freezing ambient temperature.

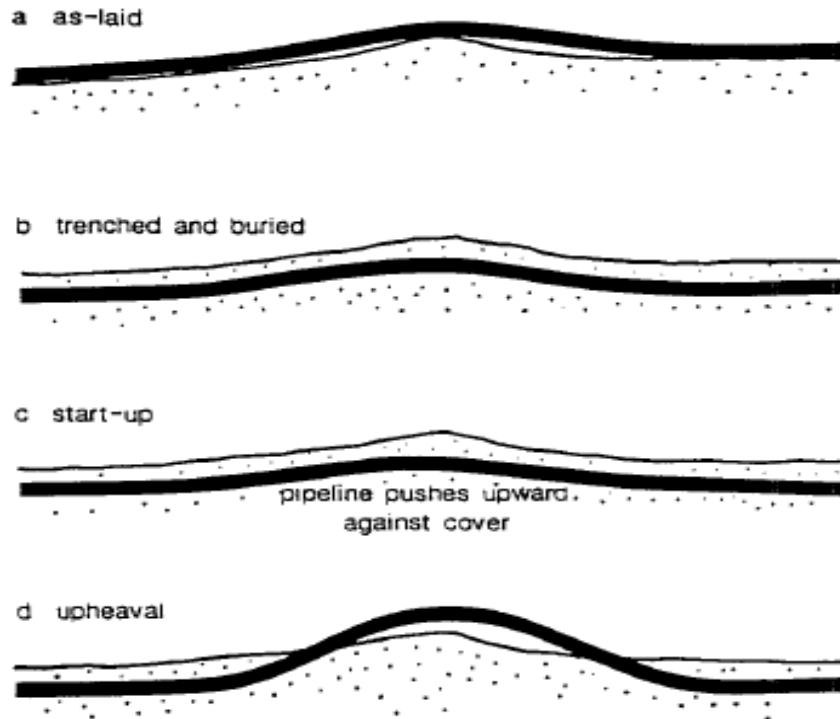


Figure 16: Sequence of laying, trenching and upheaval (Palmer et al., 1990)

The Arctic's limited open-water season delays pipeline construction. Projects involving long pipelines might require two or more open-water seasons of pipe-laying ship operations. To date, no seaward pipeline has been introduced from pipe-laying ships in ice-covered regions. If maintenance operations for subsurface pipeline and associated equipment are possible only in open-water months, the time accessible for such operations could be constrained to 1 or 2 months per year.

Ocean and fresh water freeze in winter on the Arctic shore. Water starts melting in the spring, except for sea water. If fresh water interacts with a crack, it descends through the hole, developing a spinning vortex (called a “strudel”), and the intense flow pours downward. The jet scours a hole in the seafloor. This incident may treacherously affect seabed pipelines because high-speed jets may cause deformation of the oil and gas pipeline.

Generally, offshore permafrost is natural in shallow water in the Arctic, in spite of the fact that it lies tens of meters beneath the seafloor and is induced by continuous heating from the overlying seawater. Uninsulated pipeline could be the source of potential settlement of the pipeline, and this event will induce the deformation of pipe. In regions where the offshore permafrost is intermittent, high differential settlements can happen as the pipeline settles in melting permafrost zones and stabilizes in non-permafrost zones (Hamilton et al., 2014).

Large numbers of completed pipeline projects have been operating effectively for a considerable period of time. Throughout the past few decades, piping design and operation technologies have been improved remarkably. Protecting pipelines against damage from ice is a key element for pipeline design in the Arctic region. First, the burial depth of pipelines is important. To deter pipelines from contacting with ice and producing significant gouging, the depth of burial for pipe is mainly decided by the gouge-depth database (gouge depth distribution, number of occurrences) gathered over a couple of years. Repeated ice gouge surveys are conducted during the open water months to assess the frequency and depth of ice gouge. Second, a supplementary burial depth is needed to avoid pipeline distortion by sub-gouge deformations. The goal is to guarantee that pipeline strains are restricted to avoid pipeline rupture and leak. Third, for trenching and internment of subsea pipelines, the selection of suitable equipment for offshore pipeline installation depends on properties of seabed soil, trench depth and depth of seawater. In particular, deeper seawater depths including hard masses of rock and hardened seabed soils, are very challenging. Ice-rich

permafrost coastlines are vulnerable to rapid coastal erosion throughout the Arctic region because of the thawing permafrost. Digging and operation of warm pipeline could heavily affect pipeline exposure due to the rapid coastal erosion. The Arctic pipeline installations in coastal permafrost region have adopted thaw stable material and thermosiphons to keep the ground frozen. Additionally, cofferdam has been used to keep the soil stable until the completion of pipe laying and backfilling. Pipeline tie-ins to gravity-based structures and seafloor wellheads are required to be protected from the interaction with sea ice. Numerous types of protection structures have been applied against the Arctic sea ice.

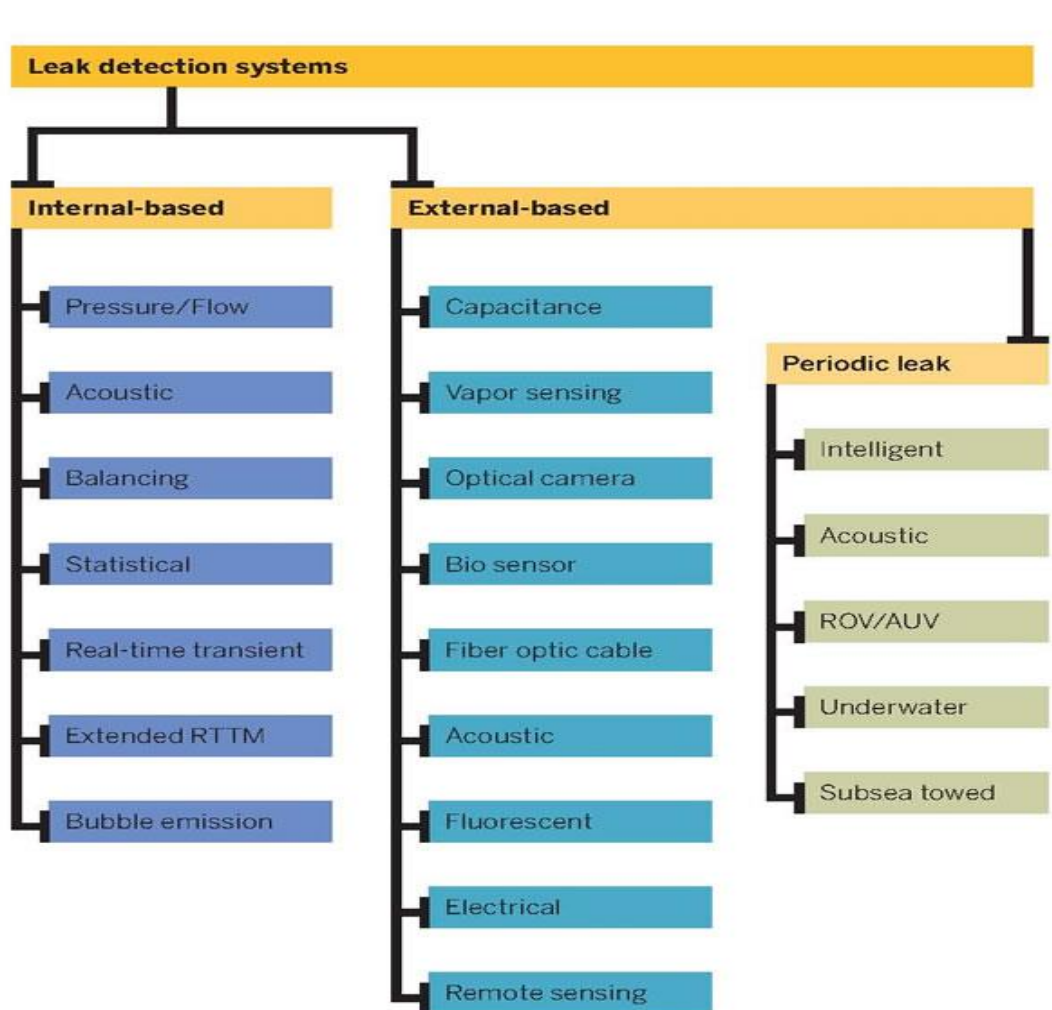


Figure 17: Sample of Arctic leak detection system (Thodi et al., 2012)

Typical pipeline surveillance can be limited by the sea ice. Therefore, an enhanced pipeline leak detection system has been proposed to operate effectively in case of oil spills. With extremely harsh conditions, Arctic pipelines must be monitored continuously. Fast and reliable pipeline leak detection including location identification are crucial features for hydrocarbon transportations. Arctic leak detection systems have introduced two-tier system: internally based and externally based. Using field data such as pressure, temperature, and flow rate, an internally based detection system quickly identifies the large leaks. In contrast, an externally based system uses physical properties around the pipelines including vapors, and temperature differentials. This system can detect small and chronic leaks and minimize the oil spills by means of isolating valve (Thodi et al., 2012).

3.3.2 Tankers

In the past decades, the utilization of tankers as means of hydrocarbon transportation in sub-Arctic area has been successful. However, reinforced international regulations such as the Oil Pollution Act and International Maritime Organization (IMO) Polar Code could affect potential tanker activities in the Arctic's marine areas. To operate in ice-covered sea, hydrocarbon tankers are constructed to the level of ice-class ships. Escorting icebreakers cut an open route through sea ice in front of the tanker. Unloading hydrocarbons from the marine platform to a vessel requires that the vessel have the ability to link to the unloading line and remain its position until the unloading activity is finished. Drift ice can be challenging when it comes to offloading activity in the Arctic sea. With an ice-management system to diminish the approaching iceberg to keep on loads on the vessel within the weight limitation, the mooring system maintaining the crude carrier in position is required to resist iceberg impacts on the carrier's hull. Transferring hydrocarbon to a vessel can be demanding because of the floating ice shelves and floating fragments of sea ice after continuous ice breaking. Approximately half a day of connection time is needed in a few iced-covered environments to

carry out hydrocarbon unloading operations.

From Cook Inlet in Alaska to the Baltic in Russian territory, hydrocarbon transportation using tankers has been performed successfully throughout the past decades in the ice covered Arctic sea. Several significant technological breakthroughs in hydrocarbon tankering transportation in sea ice have been made. The De-Kastri terminal in the Russian Arctic region transports oil through an offshore loading line to the single-point mooring system. This project was a turning point for hydrocarbon transportation in the Arctic region because of its successful year-round operation in conjunction with the Fixed Offshore Ice Resistant Oil Terminal (FOIROT). In 2013, the double acting ship concept was introduced as the fundamental transportation concept in Russian LNG projects. These largest icebreaking LNG tankers are able to sail in ice-seas with ice as thick as 2.1 m (Noble, 2014).

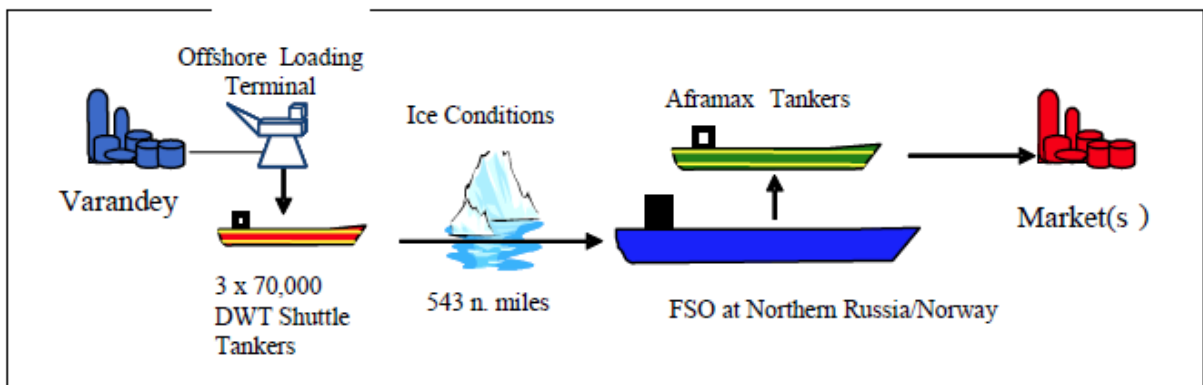


Figure 18: Transportation System Schematic (Iyerusalmskiy et al., 2007)

In the last decade, extensive global cooperation has created an international standard for the development of Polar-class vessels. This standard includes unified design, construction, and operation specifications in ice-covered conditions. New safety and environmental provisions will also be in effect in 2017. Every vessel operating in the Arctic waters will be required to follow these rules to enhance ship safety in the extremely harsh Arctic (IMO, 2014).

Safe hydrocarbon transfer from a marine platform to crude oil tankers is required to

provide highest protection against oil spills. Offloading of hydrocarbon fluid happens frequently. These activities should take into consideration ice management, including floating icebergs and sea-ice habitats. Hydrocarbon-unloading facilities including tankers have advanced technically. Training and operational experience in Arctic navigation play a significant role in improving safety and effectiveness of offloading activity. For more trained operational crews in charge of safety, navigation simulators in icy environmental conditions will be helpful. Technical accomplishments for careful offshore exploration have been made as a consequence of many years of practice and experience. In other words, prudent Arctic hydrocarbon transportation by tankers depends on choosing an effective combination of safety and cost effectiveness.

3.4 ICE MANAGEMENT

The objective of ice management is the design and safe operation of ships and equipment in ice-covered waters from the view of operation and design. The key components of ice management strategy are involved in ice detection and monitoring, ice-alert systems, and operational protocols to avoid operational disconnection from ice. Of several key factors of management system, ice detection is the most critical component. Assessment of ice-threat and following risk avoidance are required to be capable of identification of ice conditions. Information including identification of sea-ice type, operation of marine facilities, and climate are accumulated in the data management system and data are entered into the system (forecasting/ice-alert). The ice alert system will predict development of drift ice and analyze the risk to hydrocarbon production structures. To prevent ice contact from hydrocarbon production facilities, towing or breaking is used for strategic management, depending on risk and priority. If the ice management system was inadequate, the probability of interaction with ice rises (Petroleum Research, 2014).

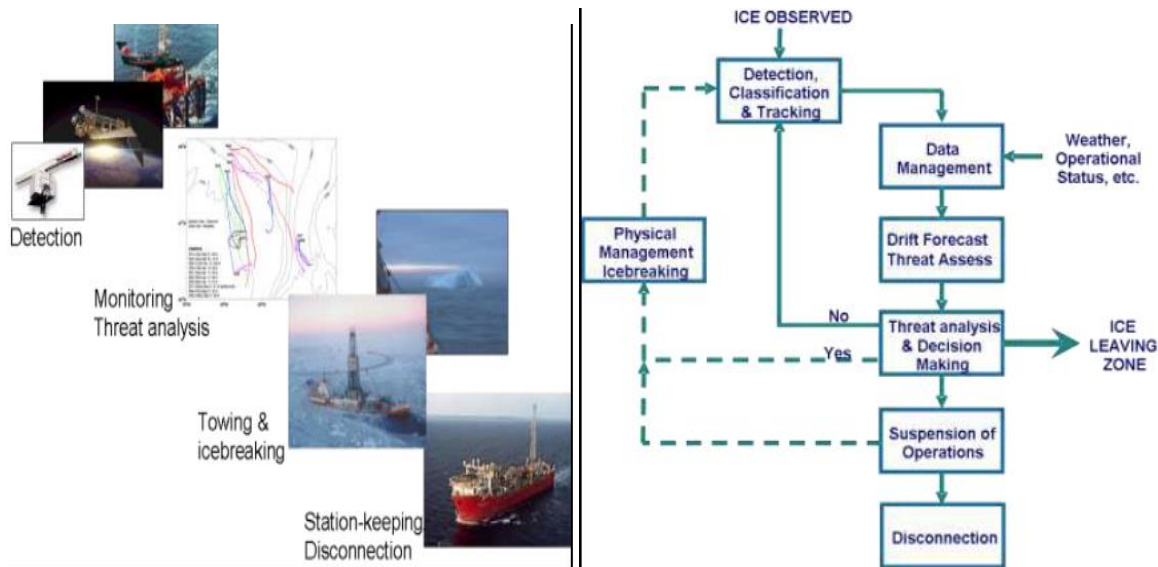


Figure 19: Ice Management Strategy and Flow Diagram (Petroleum Research, 2014)

Ice detection and monitoring plays a critical role in an ice management system. Without detection of ice, it is challenging to provide further risk prevention activities. Data including ice size, shape, and location are essential. Advanced technologies such as advanced imaging satellite, unmanned aerial vehicles (UAV), and integrated data analysis programs could further develop current ice-detection capabilities. Polar ice drift prediction includes forecasting the future directions and sizes of ice, utilizing knowledge and historical data about ice floes.

Understanding polar ice key to marine facility design and operation for effective station keeping in ice-covered waters. Ice-management-system operators are required to get the information associated with iceberg position, and seriousness of conditions for long-term prediction. To figure out the risk of each iceberg and time of operation shutdown, short-term prediction is required as well. Handling icebergs in sea ice is required to prevent towing operation delay or failure. Arctic sea ice might seriously affect sea iceberg towing. Therefore, assessing uncertainties including adequacy and methodological procedure is needed for conducting successful iceberg towing in ice-covered waters (Eik and Gudmestad, 2010).

steel chain. In case of mooring-line failure, extra lines are built to avoid disconnection. This system is widely used in shallower waters due to the economic benefit. Dynamic Positioning (DP) is a computer-aided system with multiple propellers, which are thrusters to maintain offshore facility's position against the ice loads. Thrusters might be utilized to remove the ice rubble affecting ice loads to the facility around the hull. Data collected from each sensor are provided to the computer-aided system for calculation to maintain its position of the station. Dynamic Positioning operates the propulsion system, including propellers and thrusters, from the calculation (Kokkinis et al., 2010). Characterizing ice loads accumulation regarding the contact with offshore structure is hard to figure out. Advanced experience and information on ice load would prompt a comprehensive station keeping design to operate perfectly in pack ice waters.

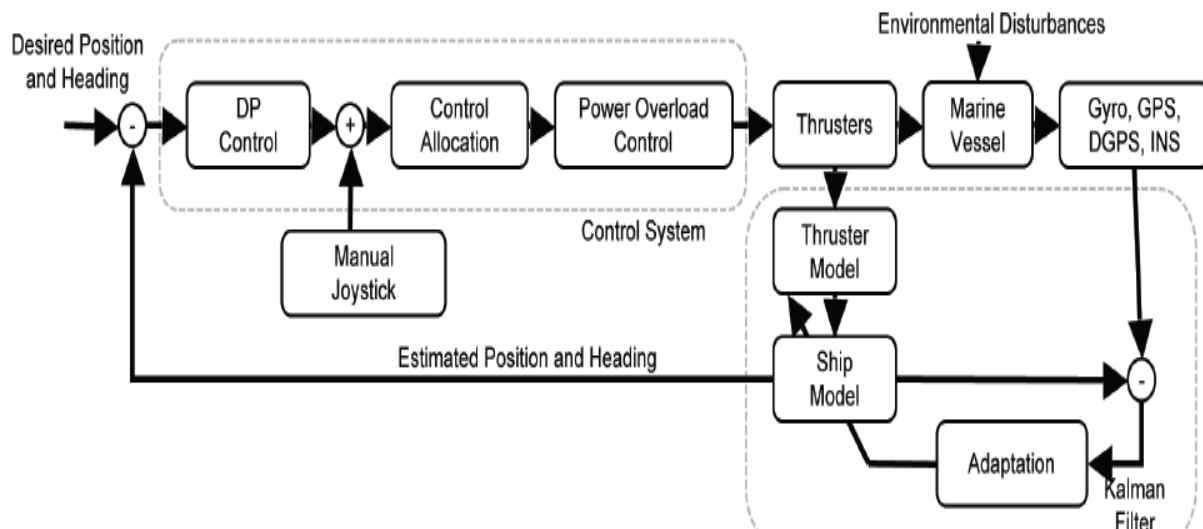


Figure 21: Flow Diagram of Dynamic Positioning (Samad et al, 2011)

Arctic sea ice condition is determined by the natural periods and regional ice condition which is closely related to outstanding ice-management strategies. First-year ice, ranging from thin ice as much as 1.5 m thick, grows to as much as 4 m of multi-year ice after repeated melting and freezing. Multi-year ice can be critically challenging in terms of breaking it effectively because of thickness and shape. Ice management with a couple of winter seasons'

exploratory activity might be complicated regarding the length of period. Ice management is a reliable tool for helping station keeping in sea ice conditions. It has been widely applied to assist floating exploratory drilling activities in the open water months until the early 1990s.

Today, ice management is able to operate properly in ice-covered conditions. In economic perspective, both ice management and ice resistant floating exploration platforms are required to be advanced to operate continuously throughout the year. Ice management system for offshore platform to ship offloading operations is less challenging than floating exploratory drilling because of relatively less complex operations.

In arctic regions, operations of ice-management strategy could be financially challenging because of the building and operating expenses associated with icebreakers. However, ice management strategy could be important in Arctic hydrocarbon development by enlarging operation periods in ice-covered waters. Exploration and production activities are securely conducted by an ice-management strategy that enables safe operations (station keeping, emergency response activity). Floating exploration platforms using ice management strategies were not operated in ice-covered waters until two decades ago.

With introduction of state-of-the-art technologies such as computer aided data processing, surveillance systems, and developed ice-resistant vessels, ice-management strategies could be improved substantially. Enhanced ice-management strategies would boost E&P operations in harsher ice environments. However, field tests should be conducted to ensure that E&P activity can continue in winter months. These tests would be a great opportunity to optimize the ice-management strategy (e.g. station keeping) of a floating exploration platform.

4. ANALYSIS OF OIL SPILL PREVENTION & RESPONSE IN THE ARCTIC REGION

Oil spills in ice-covered environments are a challenging problem for exploration and production activity. Both advanced oil spill prevention methods and response systems are required to guarantee future E&P activities in the Arctic area. Hence, oil spill prevention and response systems are prioritized when it comes to planning an exploratory operation. The oil and gas industry must consider two main concerns in designing offshore hydrocarbon facilities in the Arctic region: oil-spill prevention and oil-spill response.

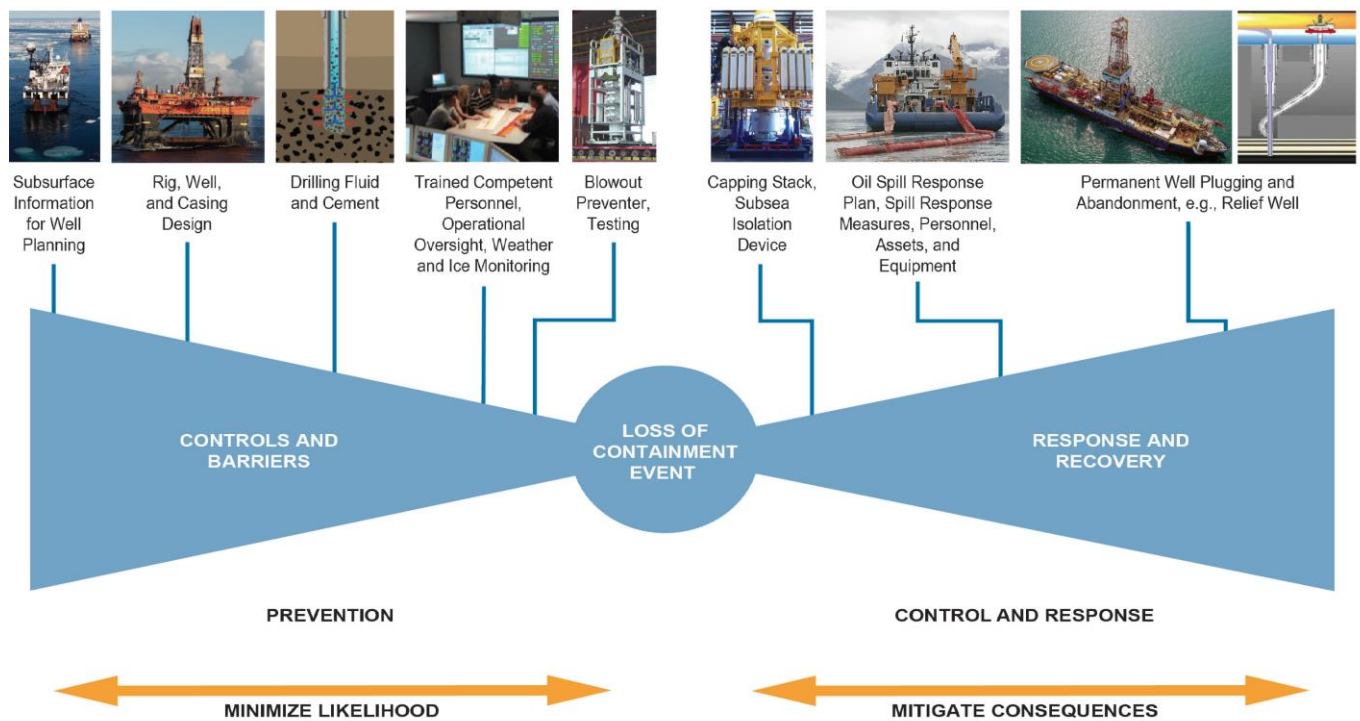


Figure 22: Offshore E&P oil spill response system and technologies (Arctic Potential, 2015)

4.1 OIL-SPILL PREVENTION METHODS

Oil-spill prevention methods with specially designed equipment and well-organized health, safety, and environmental (HSE) systems are the best prevent practice in ice-prone

areas. Offshore E&P facilities in the Arctic must have a specialized design installed to prevent oil spill in the Arctic region. Prudent design will be categorized by three prime considerations: acquisition of subsurface data, construction of subsurface wells, and correct use of drilling muds and cementing

4.1.1 Acquisition of subsurface information for E&P facility design

Exploration and Production facility design starts with acquiring the geologic information, including seismic data from the seafloor. With this, subsurface maps can be completed, showing geological obstacles such as fault planes, geologic structures, and bathymetric pressure. Shallow-hazard assessment is also carried out to identify the shallow seafloor's hazards, such as abnormal pressure zones and artificial hazards including shipwrecks and pipelines. These factors have a having substantial impact on hydrocarbon production operations. The combination of subsurface maps and shallow-hazard assessment aids in planning and constructing the new well site for prudent hydrocarbon development.

Forecasting the value of flow pressure, including thickness, depth, and fluid types is significant role in subsurface well design. Data derived from this forecasting is, then used for selection of casing strings and calculation of kick tolerance to prevent oil spills during drilling. Newly introduced technologies have enabled acquisition of updated geological data for minimizing the operational uncertainties (Moyer, 2014). These methods include Logging While Drilling (LWD), assessment of the pilot hole using weighted water base drilling fluid.

4.1.2 Subsurface well structure

In a subsurface well, the Blowout Preventer (BOP) and multiple casing strings are installed. The outer string is called structural casing, and the inner casings include conductor, surface, and protective casing. After completion of this structural casing, the conductor

casing must be set deep enough to permit the drilling fluid to circulate. Unlike the inland casings, whose role is to protect fresh water, offshore casings are mainly used to provide well control. The BOP is attached to the surface casing and the drilling riser is connected to a drilling rig. Once installation of subsurface well structures is completed, drilling mud is replaced by a salt solution and slotted production liners are made at the hydrocarbon reservoir.

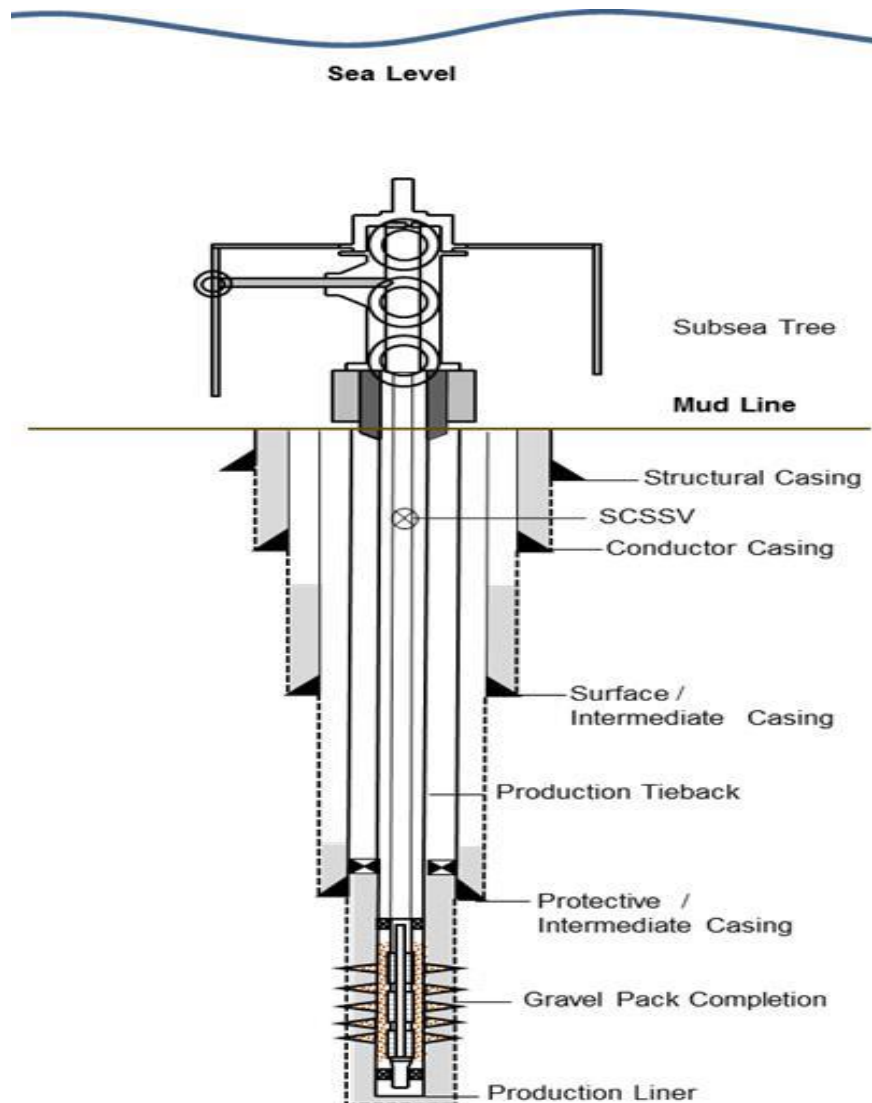


Figure 23: Subsurface drilling well – completion/production stage (Moyer, 2014)

Finally, a “Christmas” tree which is a group of valves and fittings and pipe spools, is attached to the wellhead. In subsurface conditions, additional safety equipment such as a surface-controlled subsurface safety valve (SCSSV) is applied in the event of a possible the Christmas-tree malfunction (API Spec 16A). Arctic subsea well structures are almost same as temperate offshore wells except for measures designed to compensate for hazards caused by ice-prone conditions.

4.1.3 Drilling muds and cementing

Drilling mud to avoid forced fluid inflow (kick) from the hydrocarbon reservoir is the prime element for safe hydrocarbon extraction. Depth of casing string is determined by the combined pressure (mud weight and equivalent circulating density) to prevent kicks. A pressure integrity test (PIT) is essential for well control activity. A PIT test is carried out to measure the formation strength controlled by the compressive stresses coming from underground rock (Postler, 1997). Hydrates can be made by high pressure and low temperature exerted in the offshore Arctic environment, and this phenomenon would impede fluid flow. To prevent drilling fluid freezing, non-aqueous fluids (NAF) or chemicals (glycol, methanol) are included in the fluid. As mentioned before, kick detection has greatly impacted well control associated with oil spills.

Wellhead and casing are important pressure containers for preventing blow-outs caused by high-pressure formations. Therefore, their design specifications should meet the international standards applicable to the Arctic environment. After the calculation of all loads of all equipment mounted on the wellheads, the calculated load and safety factors are applied to determine a performance rating. Quality of each component of wellheads is important as well, and it is guaranteed by the manufacturers’ quality certificates and inspection tests (factory acceptance test, site acceptance test) according to international standards (Moyer, 2014).

Cementing plays a key role in well integrity. Cement is poured into the annulus between bore hole and the casing. The required amount of cementing is calculated by instrumentation and measurement. Usually, the amount of cementing is determined by the degree of zone separation between casings except for the conductor casing.

Before cement is pumped into the well, cement composition must be adjusted to reflect ambient factors associated with environmental conditions (pressures and temperatures) of a well. After cement setting, verification tests, including PITs, should be conducted.

Advanced cement sealing techniques have been introduced in the last 20 years. For separation between the drilling mud and cement, a spacer and wiper plug are usually applied. A float collar, mounted on the bottom of casing string is installed, to avoid back-flow of cement from the casing during cement injection because of its check valve, but the float collar does not prevent hydrocarbon from flowing inside the casing (National Commission, 2011).

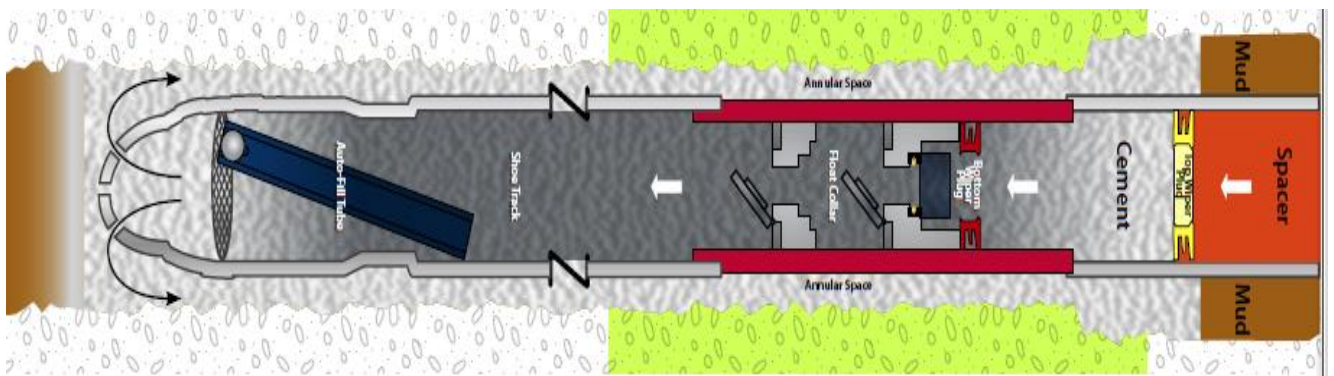


Figure 24: Cementing schematic (National Commission, 2011)

In Arctic wells, special design and construction techniques are required to deal with frozen soil when drilling. Melting permafrost could lead to concrete cracking and gas leakage. Therefore, appropriate material selection is necessary to increase performance, such as tensile strain capacity and ductility.

4.1.4 BOP and control equipment

Blowout Preventers (BOPs) are applied to control unexpected pressure in drilling muds (fluids) in a well. Several types of preventers (annular, ram, and shear rams) are equipped in BOPs to close the well from abnormal conditions. In case of subsea operations, a lower marine riser package (LMRP) is added to isolate a well from the offshore drilling rig.

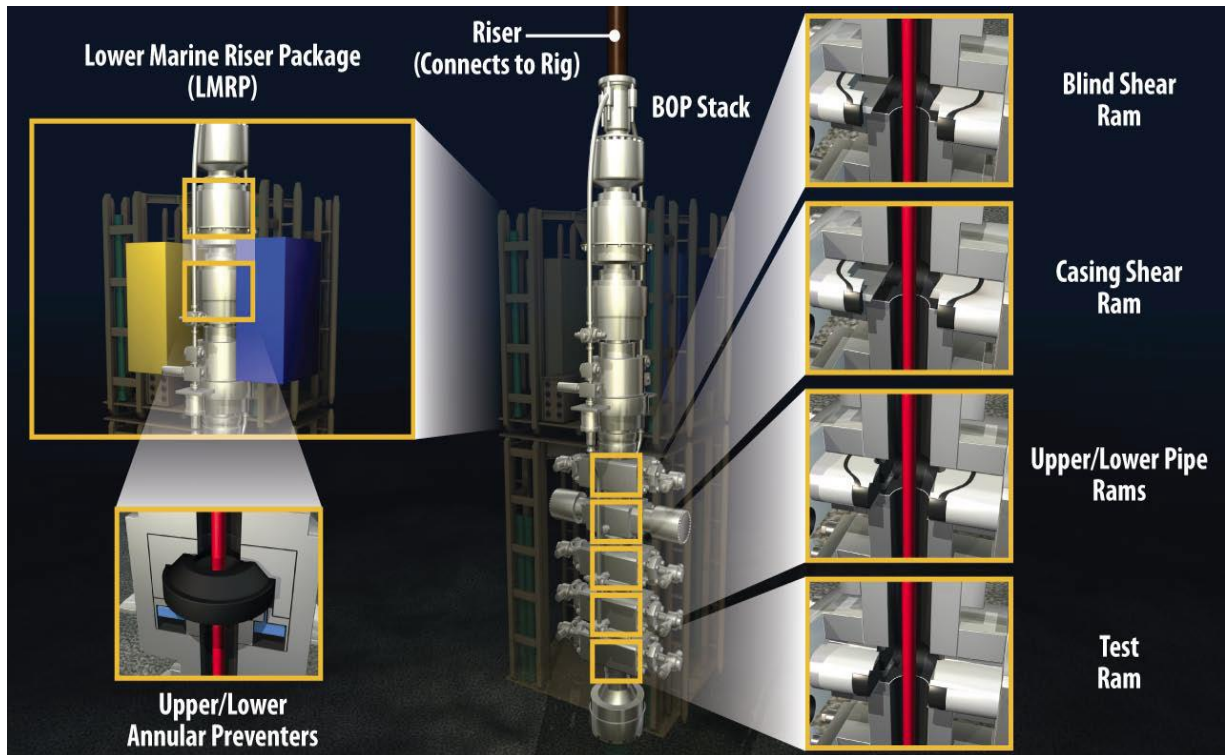


Figure 25: Typical subsea BOP stack (National Commission, 2011)

BOPs are actuated through several independent pumping methods (hydraulic, pneumatic, and electric) in case of the malfunction. Generally, BOP components are designed to operate up to 1,030 bars of working pressure in the offshore Arctic. As mentioned previously, BOPs consist of different types of preventers to provide multiple redundancy to ensure safety during hydrocarbon exploitation. After the Deepwater Horizon disaster (2010), new safety rules were put into effect. Numerous BOP tests associated with pressure have also been added (Moyer, 2014).

Responsible for providing a conduit for circulation of drilling mud from the borehole to the offshore rig, a marine drilling riser is extended to the subsurface BOPs. If there exists hydrocarbon flow in the drilling riser, annular elements start to seal around the pipe and the hydrocarbons flow back to the well via the flow diverter pipeline (Moyer et al., 2012).

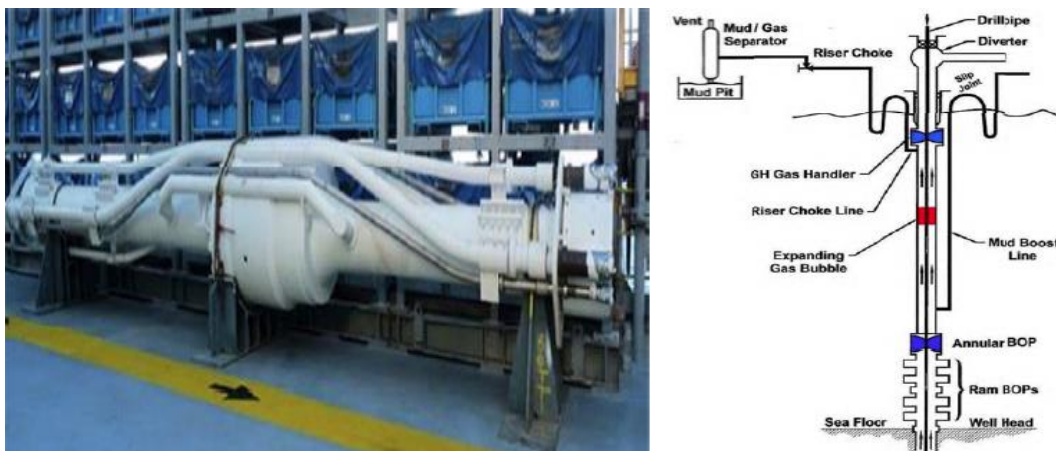


Figure 26: Riser and mud/gas separator (Moyer et al., 2012)

Detecting a kick (fluid influx) has been widely used due to safety concerns. When mud flow rate is made to fluctuate and then is identified, this is the most reliable kick detection method during drilling activities. Two sensors play a critical role to detecting kicks. A sensor called a pit volume totalizer (PVT) calculates the active drilling fluid volume. If the sensor-detected fluid level rises to a certain point, it means kick occurs and the alarm system will be activated to let operator notice. Also, fluid flow rate is an important measurement factor for kick detection. Abrupt increase of flowrate indicates the existence of a kick. Newer, mass flow meters with higher accuracy provide reliable measurement of fluid flow rate, the frequency of use would be expanded for kick detection.

Potentially pressurized zones can be found by using a mud logging system that analyzes the gas types and amounts. In offshore wells, logging while drilling (LWD) is mainly applied to identify formation pressure from the acquired geologic data.

4.1.5 Subsurface emergency devices

Using offshore well capping stacks was not routinely done until the Deepwater Horizon accident in 2010. If BOPs fail and a blowout happens, capping stacks control the hydrocarbon spills for a temporary period of time. Capping stacks equipped with sensors the monitor pressure and temperature of the well condition are actuated by hydraulic fluid (Madrid and Matson, 2014). After the Deepwater Horizon disaster, it is now apparent that using capping stacks is required, so that operators can respond to oil spills immediately.

Subsea isolation equipment is effective because of its characteristic feature of quick response in case of an oil spill. Such equipment is particularly useful in remote locations such as Arctic areas. To increase safety redundancy of subfloor E&P activities, subsea isolation equipment is operated independently from other blowout preventers. These isolation devices are similar to well capping stacks in terms of operating power source and installation methods. In harsh environments like the Arctic, these pre-installed shut-in devices would greatly enhance safety in terms of oil-spill response.

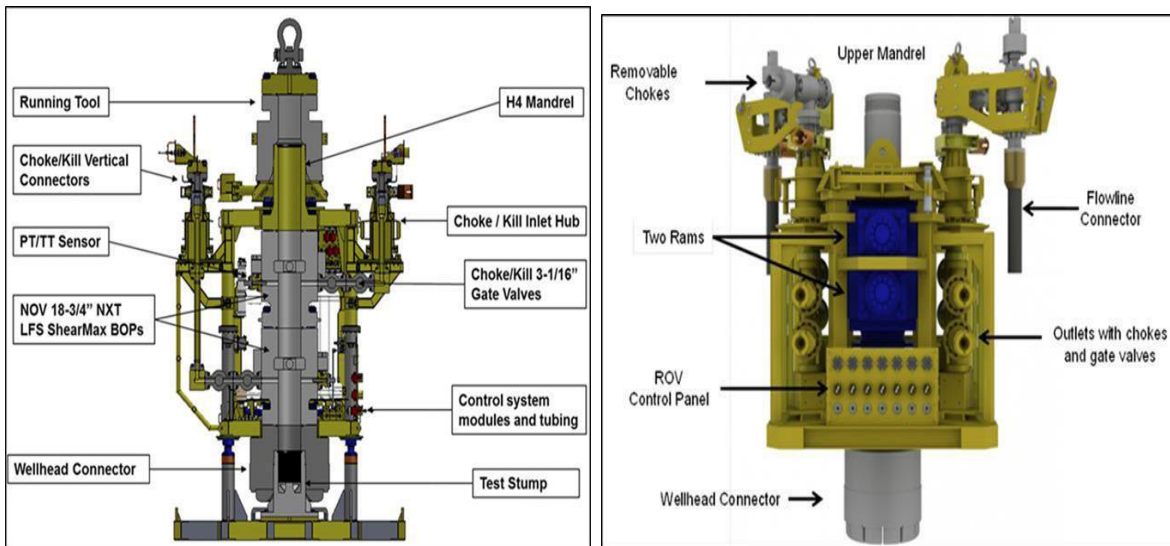


Figure 27: Capping stack and shut in device (Moyer et al, 2012)

4.2 CHARACTERISTICS OF SPILLED OIL IN ICE

Because offshore Arctic hydrocarbon E&P activities have been conducted in open sea water conditions, oil-spill responses focused on open-water conditions. Severe conditions including low temperatures and an ice-covered environment can be challenging because they significantly impact precise and effective oil-spill response in more difficult conditions.

4.2.1 Oil Spreading

Low temperatures affect oil spreading in Arctic areas, both inland and offshore. Roughness of the ice is an important factor in measuring oil spreading. The more surface roughness increases, the more oil holding capacity is enhanced. Therefore, the oil spreading area is reduced by the degree of surface roughness of the ice.

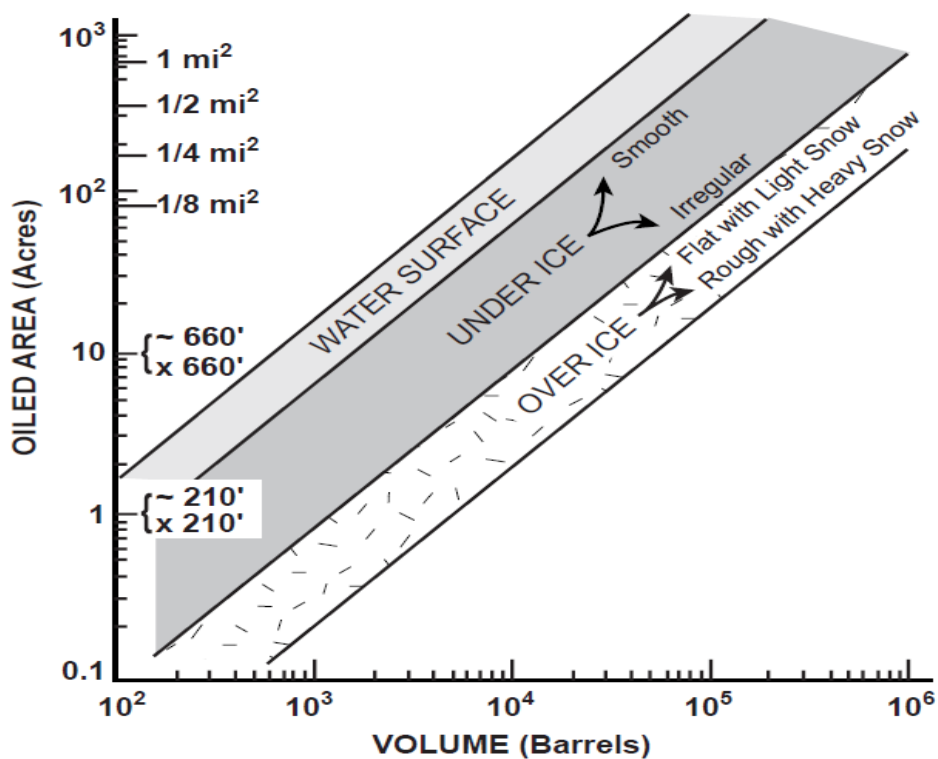


Figure 28: Typical Arctic oil-holding capacity (Potter et al., 2012)

Another critical factor for oil spreading is water temperature. Very low temperature of the Arctic of the region was not applied to the “viscosity correction factor” that was performed in temperate regions (Buist et al., 2009). If the ambient temperature reaches the pour point that a liquid (oil) loses flow characteristics, oil spreading tends to stop due to the enhancement of oil viscosity.

Numerous experimental tests have shown that oil spreading under ice-covered seas is likely to be relatively limited compared to open-water ocean currents under thick and rough ice. Oil spills occurring in areas having more than 70% ice concentration could mitigate the progress of oil spreading (Dickins, 2011).

	Open Water (<20%)	Under Solid Mid-Winter Ice	On Smooth Ice
Final Average oil Thickness (mm)	0.016	40 - 90	3
Final Area (ha)	10,000	7 - 70	50

Table 5: Oil-spreading test results comparing existence of ice as a factor in areal extent of an oil spill (SL Ross et al., 2010)

4.2.2 Oil Movement

Oil spills in an ice-covered environment are unique in that spilled-oil movement occurs along with ice, except when relatively strong currents (> 0.5 knots) exit the ice (Cammaert, 1980). Generally, currents under ice are less than 0.5 knots in winter (Potter et al, 2012). Given the unique Arctic environment (low temperature and thick ice), weathering processes and oil contamination on the shoreline are less likely to happen in Arctic areas (Dickins and Buist, 1981).

When an oil spill occurs under ice in winter, spilled oil is likely to be trapped by the

ice. Oil starts releasing after the ambient temperature increases in the Arctic (Dickins and Buist, 1981). If the temperature remains above the freezing point, oil slicks will thicken for a relatively short time (up to twice faster). Wind energy could move oil slicks to the edge of the meltwater pools and would aid in controlling the spill

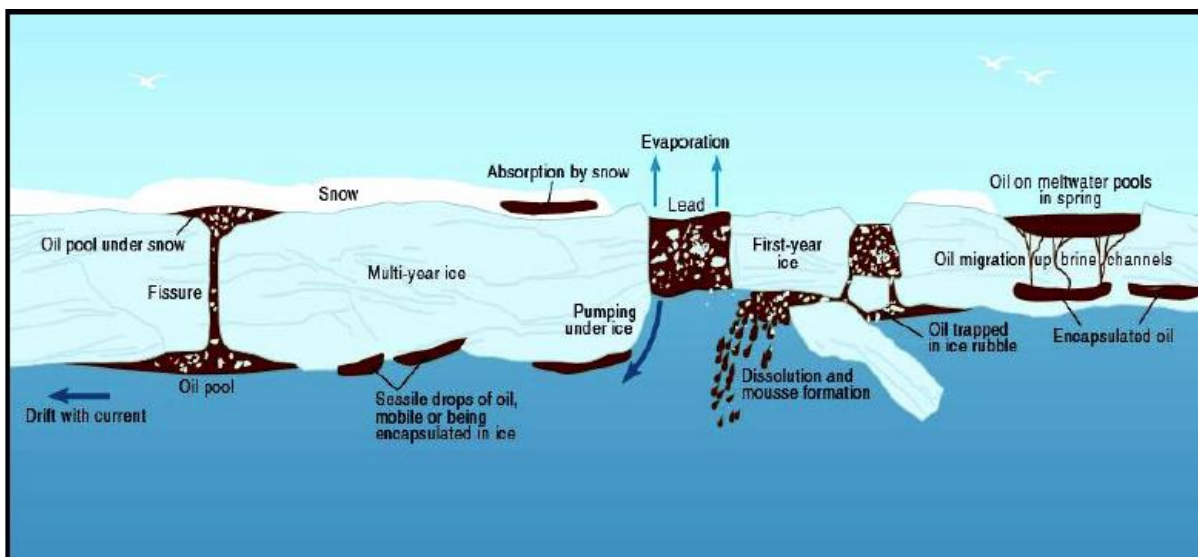


Figure 29: Typical oil-holding capacity in the Arctic (Allen, 1990)

4.3 OIL-SPILL RESPONSE

4.3.1 Oil-Spill Monitoring and Detection

An ice-covered environment has both good and bad effects. A good factor is that ice roughness can slow the oil spreading better than would happen in open-water conditions. Moreover, oil spills under the ice tend to limit oil spreading. Thus in icy environments there is less demand for frequent sensor-data updates. The bad factor in Arctic operations is that drillers' lack of understanding of oil behavior and insufficient knowledge of possible oil-spill responses could negatively affect spilled oil cleanup.

Oil-spill control in icy environments has long been a problem (Brown, 2008). Recently, researchers have found that a combination of different sensor systems could enhance

monitoring and detection (Potter et al., 2012). One possibility is to use air-borne remote sensors with visual detection by a trained crew for finding offshore oil leaks. However, field tests on oil detection and mapping capability in the Arctic have not been conducted (Anderson et al., 2010). An advantage of this system is that a radar sensor allows airborne remote sensors to conduct oil-spill detection regardless of adverse weather conditions such as fog, clouds and rain. Advanced and economical Infrared Radar (IR) technologies have been applied in airborne remote sensors. The disadvantage is its limited ability to distinguish oil spills from incorrect objectives including ocean trash (Fingas and Brown, 2011).

Satellite can identify surface objects such as oil spills on water. This significant improvement of oil detection in ice-prone waters helps in collection of data regarding varying ice conditions. Satellite radar is a popular tool because it is capable of monitoring and identifying oil spills despite atmospheric changes (Leifer et al., 2012).

Ground Penetrating Radar (GPR) is also able to identify oil slicks under ice environment (Dickins et al., 2009). GPR might be utilized with aircraft, but there are uncertainties of GPR interpretations when it comes to oil detection within the snowpack. Hence, GPR methods should be used to improve oil spill characterization (Bradford et al., 2010). Although GPR data do include oil spills, future studies could provide reliable data for oil spill detection.

As discussed above, every sensor has its own limitation. Using different types of sensors could enhance the reliability of oil-spill detection. Sensors integrated with advanced technologies including NMR imaging and GPS would definitely support monitoring and detection of oil spills in the Arctic (Nedwed et al., 2008).

Platform	Ice Surface		AUV	Shipborne		Airborne						Satellite
Sensor	Dogs	GPR	SONAR	Radar	FLIR	GPR	Visible	UV	FLIR	SLAR	ALFS	SAR
Oil On Ice												
Exposed on cold ice surface	Y	N/A	N/A	N	Y	Y	Y	N	Y	N	Y	N
Exposed on spring melt pools	Y	N/A	N/A	?	Y	N	Y	?	Y	?	Y	N
Buried under snow	Y	Y	N/A	N/A	N	Y	N	N	N/A	N	N	N
Oil Under Ice												
Smooth fast ice	?	Y	Y	N/A	N/A	Y	N/A	N/A	N/A	N	N	N
Deformed pack ice	?	?	Y	N/A	N/A	?	N/A	N/A	N/A	N	N	N
Oil In Ice												
Discrete encapsulated layer	?	Y	N	N/A	N/A	Y	N/A	N/A	N/A	N	N	N
Diffuse vertical saturation	?	?	N	N/A	N/A	?	N/A	N/A	N/A	N	N	N
Oil Between Ice Floes												
Low concentration	N/A	N/A	N	Y	Y	N/A	Y	Y	Y	Y	Y	Y
High Concentration	N/A	N/A	N	N	Y	N/A	N	N	N	N	N	N

Legend:

Y = Likely

? = Possible

N = Not likely

N/A = Not applicable


 = Blocked by dark/
clouds/fog/precipitation

Table 6: Applicability of sensor technologies for oil spills (Dickins et al., 2010)

4.3.2 Mechanical Recovery

Mechanical recovery including containment, is the process of removing spilled oil floating on the water by using skimmers or insoluble materials (Potter et al., 2012). Mechanical oil removal has a great advantage because this cleanup could mitigate environmental problems related to oil-spill response (SL Ross, 2010). For mechanical recovery, encounter rate (the amount of spilled oil which comes into encounters a recovery equipment) is a key factor in removing spilled oil effectively. In case of windrows (the oil slick gets thinner) occurs, encounter rate would be seriously reduced by wind and ocean currents (NOAA, 2007). Mainly, mechanical recovery has been efficiently used for limited areas or small amounts of spilled oil.

In the event of open-water oil spills, mechanical oil removal could be very challenging because oil spills are likely to be dispersed quickly. Generally, open-water oil spills tend to

spread out quickly to enhance oil concentration in open-water conditions, oil containment equipment is critical for successful oil recovery. Therefore, containment booms are designed to be placed rapidly and are manufactured to be utilized in cold weather to avoid boom distortion.

Older containment booms are carried out under the speed of 1 knot to contain spilled oil effectively (Coe and Gurr, 1999). This relatively low speed operation could negatively affect oil recovery. Current boom systems have greatly improved the speed limitation. Several field tests have demonstrated that advanced boom systems could operate efficiently at a higher speed (up to 5 knots) (USCG, 2001). The introduction of boom vanes has reduced the number of operating ships. Boom vanes are useful for quick deployment and excellent positioning of containment booms (Mandler, 2001).

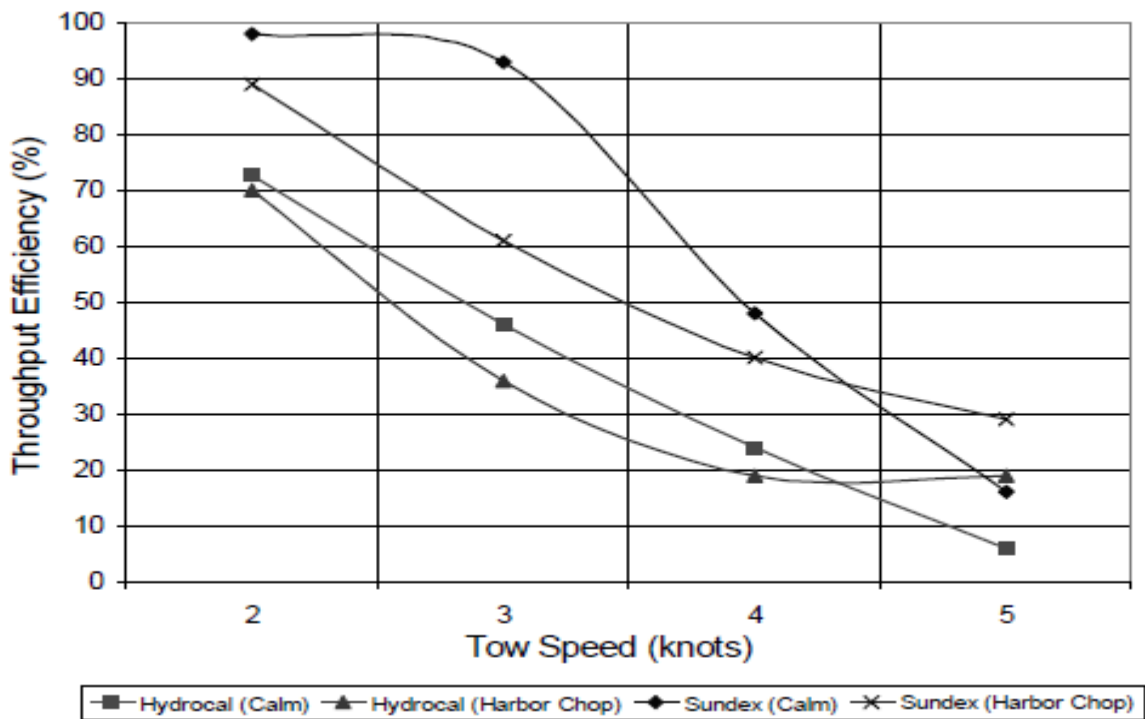


Figure 30: Throughput efficiency vs. tow speed (Mandler, 2001)

Today, four different types of skimmer systems are commercially available for offshore oil recovery (Potter et al., 2012). Oleophilic skimmer systems, consisting of belt, drum, disc and brush have high recovery efficiency (90% of oil-to-water ratio) with low recovery rates

compared to weir skimmer devices. Usually, this system is useful to recover oil ranging from low to medium viscosity. Weir skimmer systems are most widely used in marine oil spills. Regardless of its popularity, this system's relatively low recovery efficiency (50%) needs more recovered liquid (mixture of oil and water) storage capacity than does the Oleophilic type. Vacuum skimmer systems uses suction to move oil upward from the water. This system has an excellent storage capacity but low recovery efficiency (less than 50%) which can be a problem. Finally, mechanical skimmer systems are suitable for oil having high viscosity.

Skimmer		Recovery rate	Oils	Sea state	Debris
Oleophilic	Disc	Dependent on number and size of discs. Tests show grooved discs can be highly effective.	Most effective in medium viscosity oils.	In low waves and current can be highly selective with little entrained water. However, can be swamped in choppy waters.	Can be clogged by debris.
	Rope mop	Dependent on number and velocity of ropes. Generally low throughput.	Most effective in medium oils although can be effective in heavy oil.	Very little or no entrained water. Can operate in choppy waters.	Able to tolerate significant debris, ice and other obstructions.
	Drum	Dependent on number and size of drums. Tests show grooved drums are more effective.	Most effective in medium viscosity oils.	In low waves and current can be highly selective with little entrained water. However, can be swamped in choppy waters.	Can be clogged by debris.
	Brush	Throughput dependent on number and velocity of brushes. Generally mid-range.	Different brush sizes for light, medium and heavy oils.	Relatively little free or entrained water collected. Some designs can operate in choppy waters, others would be swamped in waves.	Effective in small debris but can be clogged by large debris.
	Belt	Low to mid-range.	Most effective in medium to heavy oils.	Can be highly selective with little entrained water. Can operate in choppy waters.	Effective in small debris but can be clogged by large debris.
Non-Oleophilic	Vacuum/suction	Dependent upon vacuum pump. Generally low to mid range	Most effective in light to medium oils.	Used in calm waters. Small waves will result in collection of excessive water. Addition of a weir more selective.	Can be clogged by debris.
	Weir	Dependent upon pump capacity, oil type etc. Can be significant.	Effective in light to heavy oils. Very heavy oils may not flow to the weir.	Can be highly selective in calm water with little entrained oil. Can be easily swamped with increase in entrained water.	Can be clogged by debris although some pumps can cope with small debris.
	Belt	Low to medium.	Most effective in heavy oils.	Can be highly selective with little entrained water. Can operate in choppy waters.	Effective in small debris. Clogged by large debris.

Table 7: Generic characteristics of skimmer systems (ITOPF, 2012)

Generally, mechanical recovery activities are limited to open water (less than 10%) due to the effectiveness (Potter et al., 2012). But, natural containment by ice could prevent oil

spills from spreading and dissipating. This natural barrier is a great opportunity for oil-spill response because oil recovery can be efficiently carried out in a relatively small region. Also, ice could impede wave actions created by wind, and consequently, oil spills will maintain higher thickness.

Mechanical recovery in ice laden environments is required to deal with several problems associated with ice and low temperatures (Johannessen et al., 1996). First, deployment of mechanical recovery unit including skimmers and booms can be challenging due to the presence of ice and other weather conditions. Second, oil separation from ice could be a problem when recovering spilled oil in ice covered water with very low temperature. The mixture of oil and ice could create different problems, from oil recovery efficiency to the storage capacity of a vessel. Third, ice contamination by mechanical recovery activities increases and oil-smear ice can negatively affect the arctic ecosystem. Finally, extreme arctic environments have a great impact on mechanical recovery operations. In particular, the moving parts and jamming of mechanical equipment could lower both efficiency and effectiveness of oil spill response. As discussed above, mechanical recovery in ice-covered environments needs to be considered carefully. The use of mechanical recovery system is determined by recovery and encounter rates (Potter et al., 2012).

4.3.3 In-Situ Burning

For the past five decades, in-situ burning has been studied and applied to oil spill response. Regardless of its potential effectiveness in oil removal, in-situ burning has been widely applied after the invention of fire-resistant booms. In situ burning is considered to be the most effective oil spill response in icy conditions. Ice can be a natural barrier to deter oil spreading and to impede wave actions that difficult oil ignition (Allen and Ferek, 1993). In spite of its effectiveness in ice-covered environments, in-situ burning must be used cautiously,

not only for environmental reasons but also for human health effects (Campbell et al., 1994).

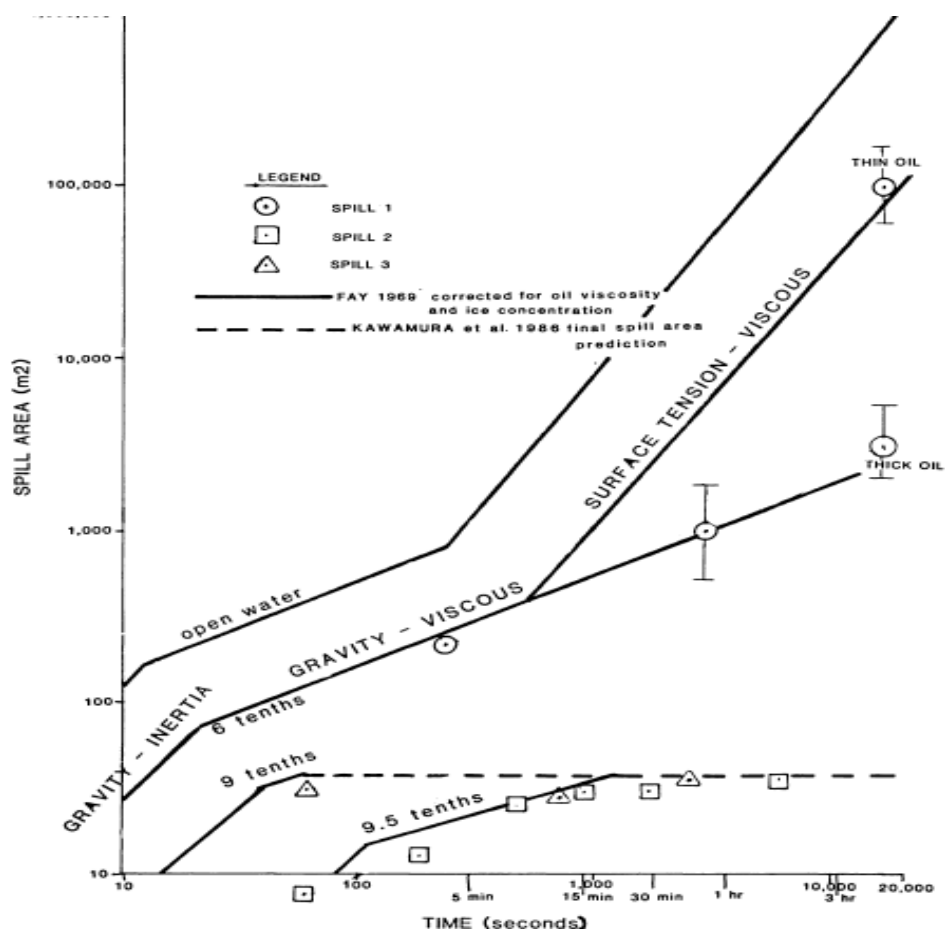
Spilled oil, oxygen, and an ignition source are main elements for precise burning. A source of ignition supplies heat to spilled oil slicks for combustion. Enough oil thickness (>0.1 inch) is a prime factor for continued oil combustion (Allen and Ferek, 1993). If the oil slicks are less than required thickness, burning activity will cease. In addition to thickness of oil slicks, excessively windy conditions (<10 to 12 m/s) and content of emulsified water (less than 25%) are key elements (Guénette et al., 1995). After the failure of an in-situ burning oil by the Exxon Valdez, emulsified water content has been studied (Sveum and Bech, 1991). A field-based experimental outcome showed that very low water content could create high burning efficiency (>90%), and recent research found that spills in fragile ice could burn for long time due to the combination of slow oil spreading and weathering (Sorstrom et al., 2010).

Factors	Description	Remarks
Emulsified water content	Maximum content (<25 %)	Burning rate and efficiency ↑ as water content ↓
Wind speed	Maximum (<12 m/s)	-
Thickness of oil slicks	Minimum(>0.1 inch)	Burning rate and efficiency ↓ as Thickness ↑
Wave action	-	Burning rate and efficiency ↓ as wave action ↑

Table 8: General in-situ burning factors for successful oil response (Modified from ROSS, 2012)

Although in-situ burning is regarded as one of the most effective oil-spill responses, effectiveness might vary, depending on the ice concentration. Effectiveness is mainly divided by three ranges of ice concentration. Ice concentration of less than 30% is similar to open-water conditions including oil spreading. In a middle range of ice concentration (30% - 70%), oil spreading and movement are reduced. To burn spilled oil effectively, deployment of

booms is required. For effective in-situ burning, more than 70% of ice concentration is required (Buist and Dickens, 1981).



Spill number	Volume of oil				
	Released (m ³)	Evaporated	Burned	Recovered	Total
1	1	25% of thick 30++% of thin	0	0	25+%
2	1	5%	77%	5%	87%
3	1	4%	80%	0	84%

Figure 31: In-situ burning efficiency regarding ice concentration (Buist et al., 1981)

Successful oil ignition on ice water requires two critical elements. To initiate burning, sufficient source of ignition should be supplied. In addition, spilled oil must be heated to maintain ongoing combustion during the oil-removal process. Spilled oil quality will be

critical to start burning. Unlike refined oil, chemically modified oil by weathering or emulsification could require pre-heating for burning (Buist, 2004).

Initially created as a device for forest fires, the Helitorch has been effectively used in several field tests (NRT, 1995). Mainly, gasoline is used as the fuel, although different types of fuels can be applied, depending on spilled-oil conditions, to facilitate ignition (Guénette and Sveum, 1995).

Hand throwing devices are also utilized with different types of fuels. These devices are designed to have time-delayed ignition for stabilized burning. For relatively small oil spills, *ad hoc* ignitors are commercially available, and various fuels can be used in different oil conditions (Guénette et al., 1997).

In offshore arctic regions, booms are critical in areas of low ice concentration. Unlike booms used for mechanical recovery, fire-resistant equipment is essential for oil containment and fire-damage resistance. To keep containment booms from being damaged, two different types of methods are utilized. One is related to materials (stainless steel, ceramic fiber) that resist to fire damages. The other type provides coolant to keep boom equipment within operating temperatures (ASTM F2152).

Despite its effectiveness in oil removal activities, there is a concern about environmental impact. Especially, air pollution caused by burning oil needs to be considered. The significant amount of pollution after in-situ burning would be carbon dioxide (CO₂). Other combustion products are also generated in small amounts. Numerous studies and field tests have been conducted to calculate the air pollutants from an in-situ burning (Johnson et al., 1991).

Constituent	Quantity Emitted ^b , (kg emission/kg oil burned)
carbon dioxide (CO ₂)	3
particulate matter	0.05 - 0.20 ^{c, d}
carbon monoxide (CO)	0.02 - 0.05
nitrogen oxides (NO _x)	0.001
volatile organic compounds (VOC)	0.005
polynuclear aromatic hydrocarbons (PAH)	0.000004
^a updated from ref. 1 based on Kuwait pool fire (Allen and Ferek 1993) and NOBE data (Ross et al. 1996) ^b Quantities will vary with burn efficiency and composition of parent oil ^c for crude oils soot yield = 4 + 3 lg(fire diameter); yield in mass %, fire diameter in cm (Fraser et al. 1997) ^d Estimates published by Environment Canada are considerably lower, ca. 0.2 to 3% for crude oil (Fingas 1998)	

Table 9: Calculated rates of emission for an in-situ burning (Buist, 2004)

4.3.4 Dispersant

Chemical dispersants are intended to minimize the environmental and economic challenges of oil spills. They promote natural dispersion by breaking the spilled oil slicks into small droplets (less than 100 microns) (Prince et al., 2013). Dispersant is a powerful oil removal option for offshore oil spills and numerous experiments and actual spills have proved its effectiveness. Contrary to mechanical recovery, dispersants can be applied to wider areas and oil removal is quite effective in the event of extremely bad sea conditions (Potter et al., 2012).

Like dish soaps, chemical dispersants have similar properties to reduce surface tension of oil slicks. When mixing energy is added including water wave, oil slicks are separated into very small drops. Capacity to disperse spilled oil is significantly determined by viscosity. Hence, the use of chemical dispersants should be carried out before weathering or emulsification (SL Ross et al., 2012). Because of their rapid response and wide coverage, dispersants can be applied along with other oil-spill remedies.

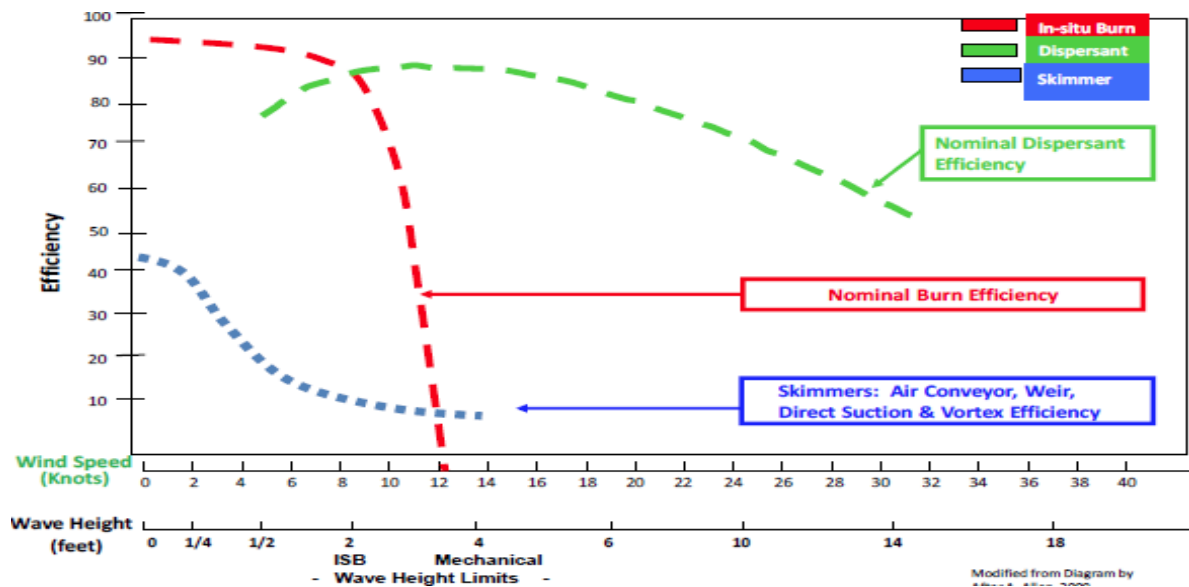


Figure 32: Response system efficiencies vs. wind speed and wave height (Allen, 2009)

Chemical dispersants are mainly designed to maximize oil removal in waters and to prevent oil from intruding on shorelines. However, the usage of dispersants could lead to increased hydrocarbon concentration in the water column. In particular, dispersant application in shallow waters needs to be considered carefully because it might affect marine ecosystems (Chapman et al., 2007).

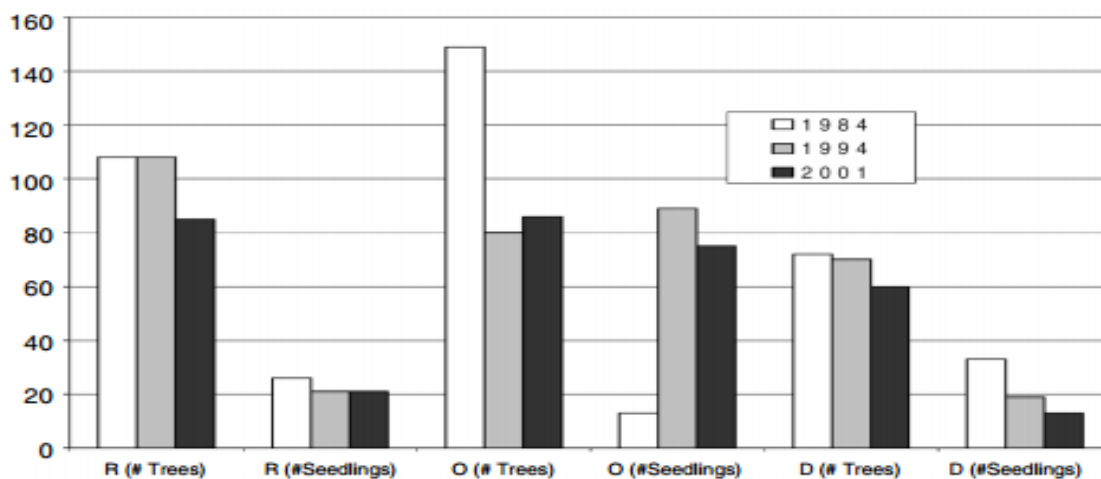


Figure 33: Result of 18 years of monitoring impacts to mangroves. Site R (reference site), Site O (whole oil), and Site D (dispersed oil) (Ward et al., 2003)

In arctic conditions, viscosity of hydrocarbons is apt to increase due to cold environments. This could be a barrier to the use of chemical dispersants in cold regions. Numerous experiments have proved that low temperature could increase viscosity, but temperature had little impact on dispersant efficiency (Farmwald and Nelson, 1982; Byford, 1983; Belore et al., 2009). Data showed that dispersants are effective until viscosity (<6,500 cP) and pour point reach certain limits. Dispersants was still effective even in freezing conditions (Belore et al., 2008). Studies of effective dispersion of viscous hydrocarbon have been conducted (Nedwed et al 2008), and more research would enhance the use of dispersants application in extreme environments including Arctic regions.

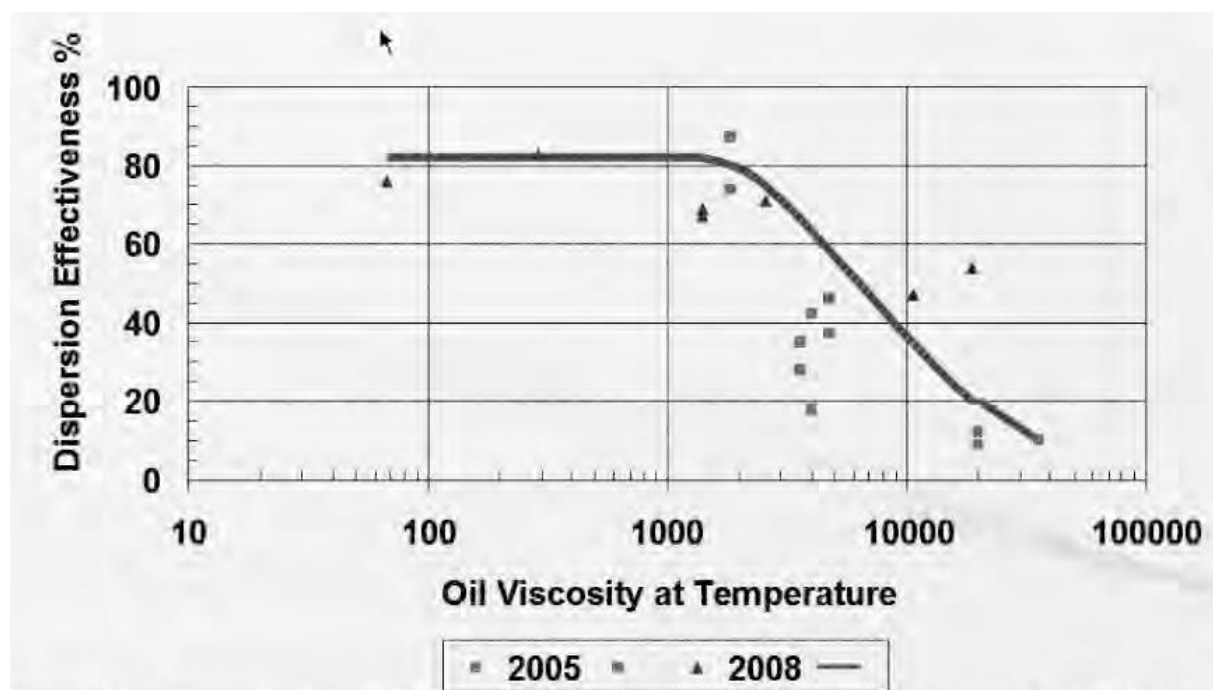


Figure 34: Dispersant effectiveness versus oil viscosity (Clark et al., 2009)

In ice covered waters dispersant application can be a trade-off because ice could hamper the mixing energy by sea waves and could delay the weathering process. Recent tests demonstrated that a certain amount of ice concentration could be sufficient for dispersants application (Sørstrøm et al., 2010).

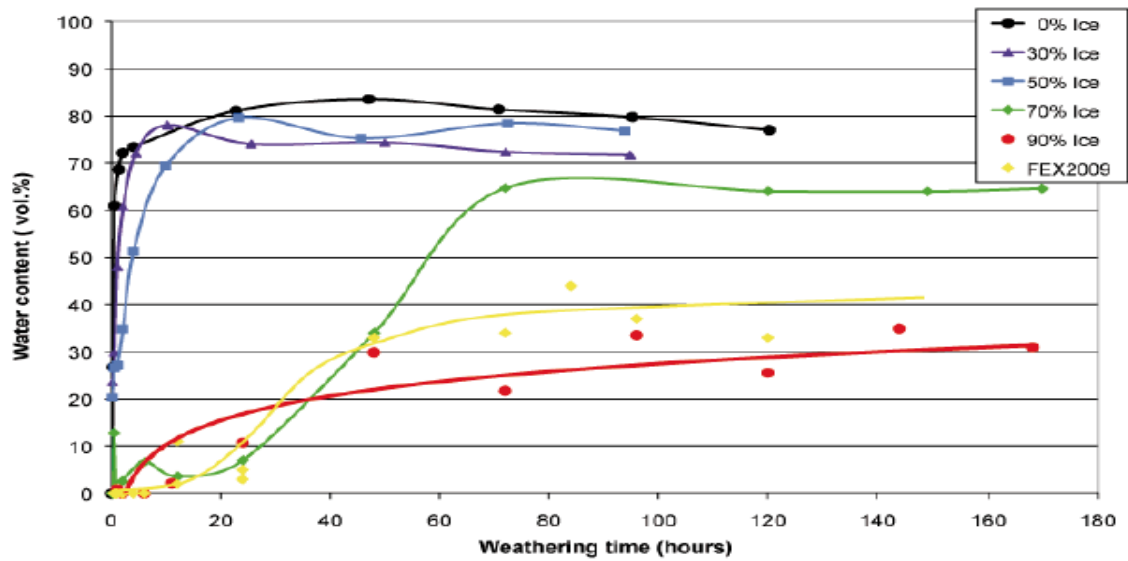


Figure 35: Water content vs. ice concentration (SINTEF, 2010)

However, additional mixing energy, including a ship's propeller, is required for a successful oil removal using chemical dispersants in highly ice concentrated waters. Mixing energy performs well in dispersion of spilled oil compared to non-mixing energy conditions (Spring et al. 2006).

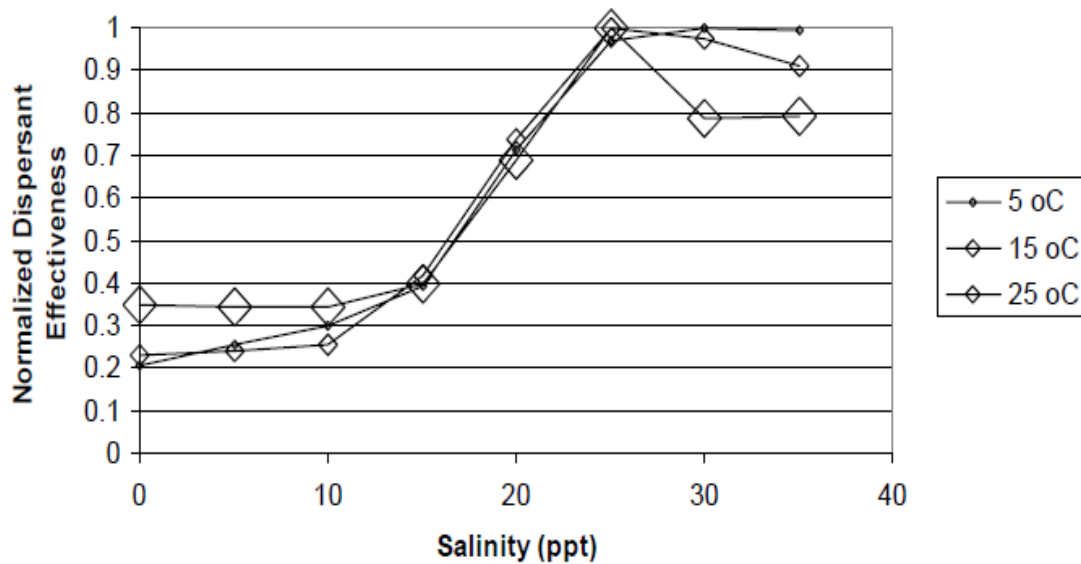


Figure 36: Dispersant effectiveness in terms of seawater salinity (SL ROSS, 2010)

In addition to ice concentration, salinity is a key factor in oil removal using chemical dispersants. Effective application of the dispersants ranges from 25 to 50 parts per thousand (ppt, ‰) (SL ROSS, 2010). Usually, regions of low salinity sea water lie near shorelines. Therefore, the use of dispersants should be prudently done near shorelines, not only for marine ecosystems but also for the dispersants' effectiveness. Recently, advanced dispersants have been tested successfully in relatively low salinity conditions (Lewis et al., 2007). Before oil removal activities with dispersant application, salinity conditions should be prudently considered.

The use of dispersants in marine oil spills is required to examine its toxicity. According to Environment Canada, toxicity of dispersants is less harmful than toxicity of typical dish soap. Spilled oil can be more dangerous to marine species than dispersants (NRC, 2005)

Product	Rainbow Trout 96 hour LC ₅₀ (ppm)
Palmolive dish soap	13
Sunlight dish soap	13
Mr. Clean cleaner	30
Citrikleen XPC cleaner	34
Enersperse 700 dispersant	50
Lestoil cleaner	51
Corexit 9527	108
BP 1100 WD	120
Oil Spill Eater bioremediation product	135
Corexit 9500	354
BP 1100X AB dispersant	2900
*Note that lower LC₅₀ defines greater toxicity	

Table 10: Comparison of aquatic toxicity of household cleaners to dispersants (Fingas et al., 1995)

During the Deepwater Horizon disaster, huge amounts of dispersants were applied in oil-spill response. Studies showed that dispersants application in 2010 Macondo oil spills has not negatively affected marine species. Moreover, the overall fish species has increased than previous years (Fodrie and Heck, 2011). Despite this optimistic result, more studies on the impact of dispersants on marine ecosystems are needed.

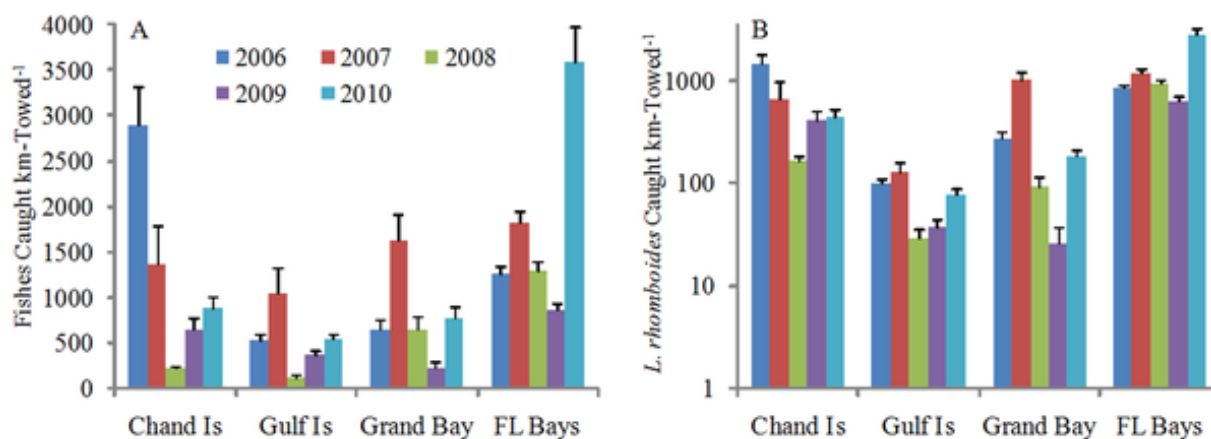


Figure 37: Catch rates of juvenile fishes (Fodrie and Heck, 2011)

5. OIL SPILL RESPONSE IN CANADIAN BEAUFORT SEA

The objective of this chapter is to analyze oil-spill responses in the Canadian Beaufort Sea in terms of temperature, ice concentration, and the Arctic environments.

5.1 TEMPERATURE

Air temperature greatly affects ice concentration in the Arctic region. To get reliable results, historical data within a long period time is needed to determine the exact ice concentration at different temperatures. Canada's Beaufort Sea has a relatively regular daily air temperature pattern, as shown in figure 38. According to Canadian Ice Services (CIS), temperature rises around 15°C in the summer and the low temperature is -40°C in the middle of winter. Historically, a high temperature of 23°C in July (1993) and a low temperature to -47°C was recorded in 1924 (Figure 39). Data show that temperature rises above zero after May and remains there until the end of September (Figure 39)

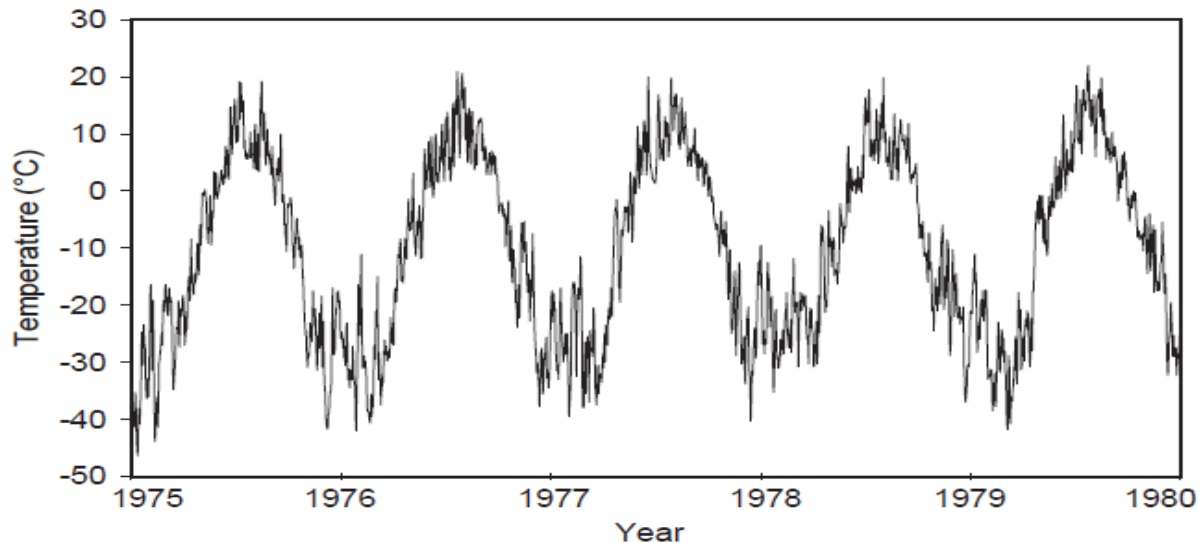


Figure 38: Mean daily air temperature at Tuktoyaktuk (Timco and Frederking, 2013)

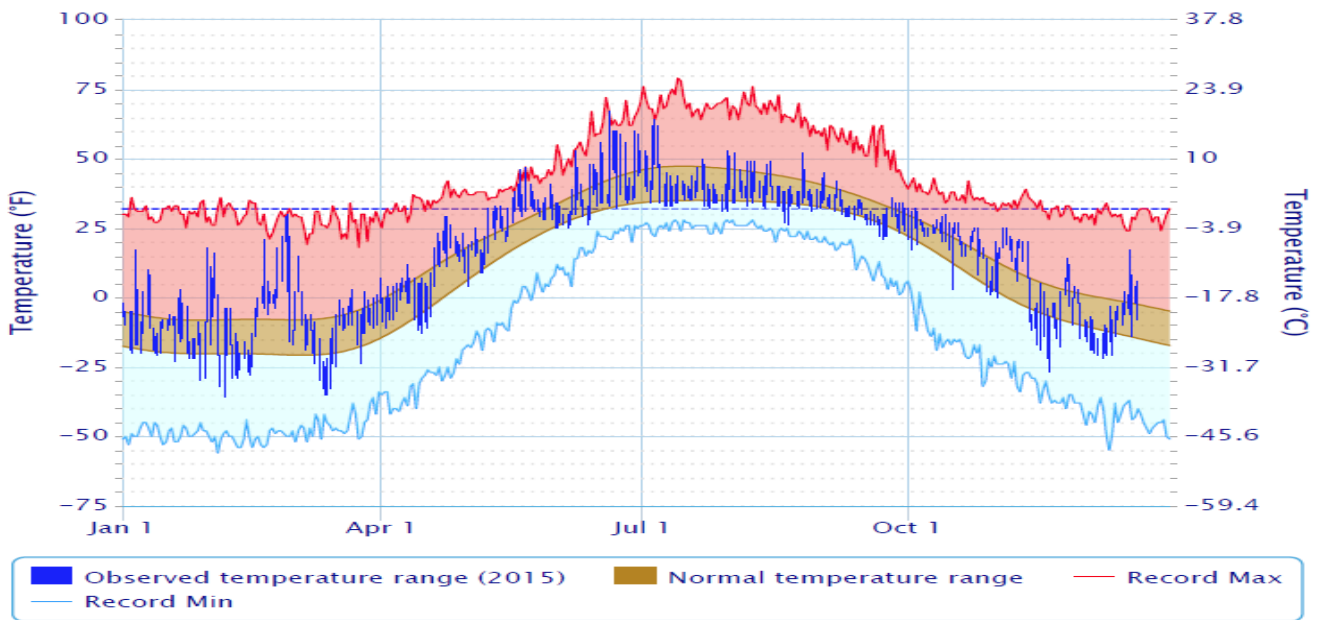


Figure 39: Yearly temperature data from 1922 to 2016 (NOAA)

Some uncertainties exist about abnormal temperature changes, but the graph in Figure 38 shows consistent temperature patterns within each season. Recent temperature data (acquired in 2015) also show a similar pattern, with normal temperature ranges. Arctic areas have very short sunlight duration during the winter. The Beaufort area has about 3 months of no sunlight (Figure 40). No sunlight in winter causes temperature drops in the area.

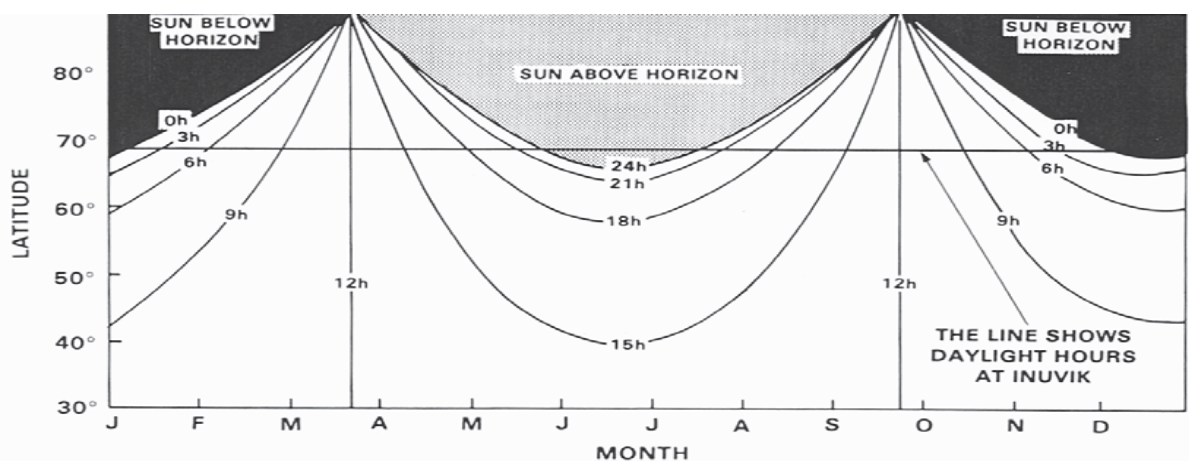


Figure 40: Number of daylight hours as a function of latitude (Burns, 1973)

5.2 ICE CONCENTRATION

In the Beaufort Sea, the ice can be grouped into three areas: an Arctic polar pack zone, a seasonal zone, and a land-fast ice zone (Kovacs and Mellor, 1974). The Arctic polar pack zone consists of relatively thick, multi-year ice (<4.5m). Generally, this zone is located 200 km away from the Canadian onshore. The seasonal zone, situated between the Arctic polar zone and the land-fast zone, ranges from several kilometers to hundreds of kilometers in length (Spedding, 1978). This region consists mainly of first-year ice, with a small amount of multi-year ice.

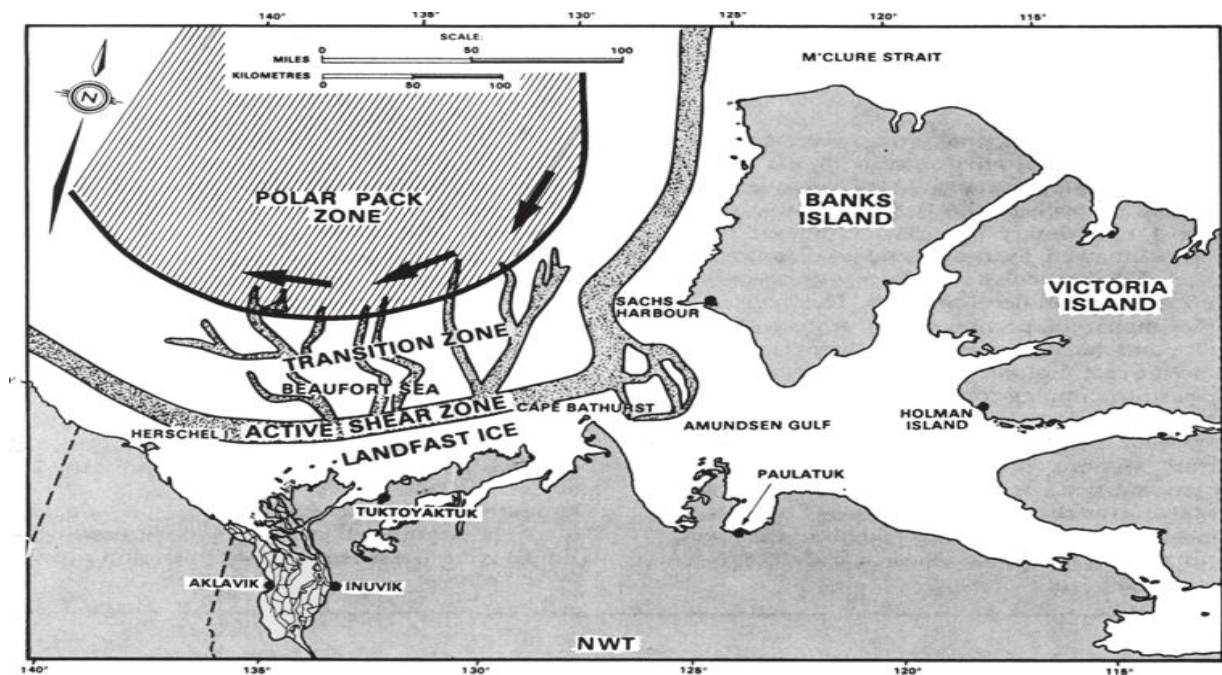


Figure 41: Three zones of ice in the Beaufort Sea (Kovacs and Mellor, 1974)

The land-fast ice zone is usually restricted to relatively shallower waters (<30m deep). This zone dominantly consists of first-year ice, and it has been mapped as having moved as the temperature goes down (Figure 42). The ice starts developing in late September and melts in June (Figure 43).

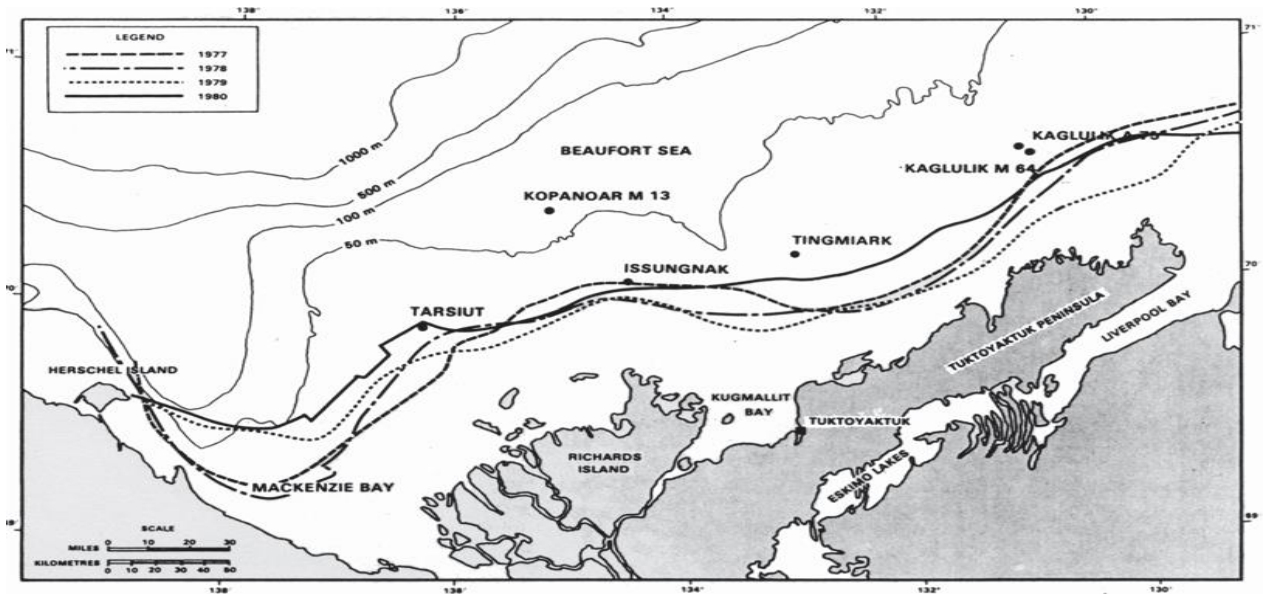


Figure 42: Progress of the landfast ice from 1977 to 1980 (Spedding, 1978)

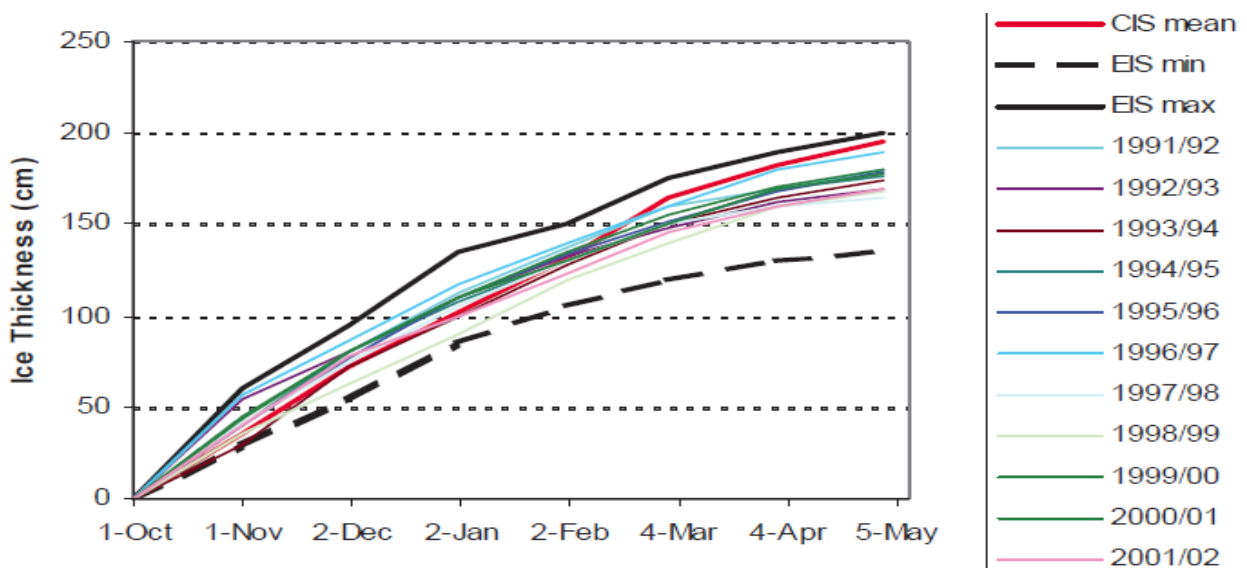


Figure 43: Ice thickness in the Beaufort Sea (Devon, 2004)

To analyze the ice concentration in Beaufort Sea, many years of sea ice development data were used. In this study, selected (1984, 1994, 2004) data were used to determine average sea ice concentration. The data were acquired from Amundsen Gulf in the Beaufort Sea. Over 70% ice concentration occurred during week 41 (beginning of October), and melting occurred during week 23 (the beginning of June) (Figure 44).

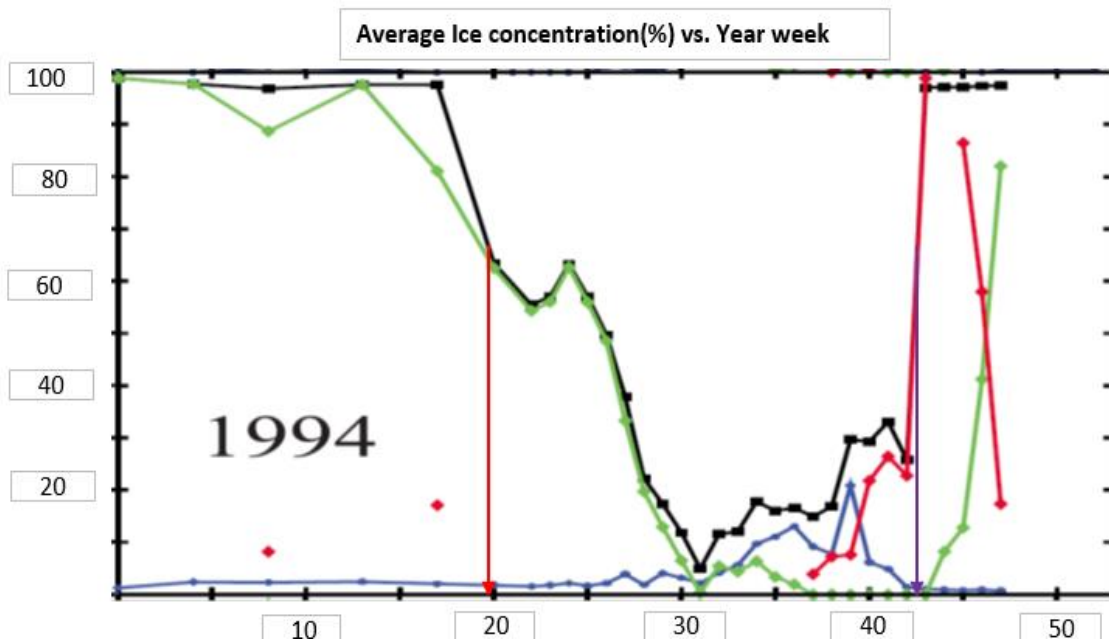
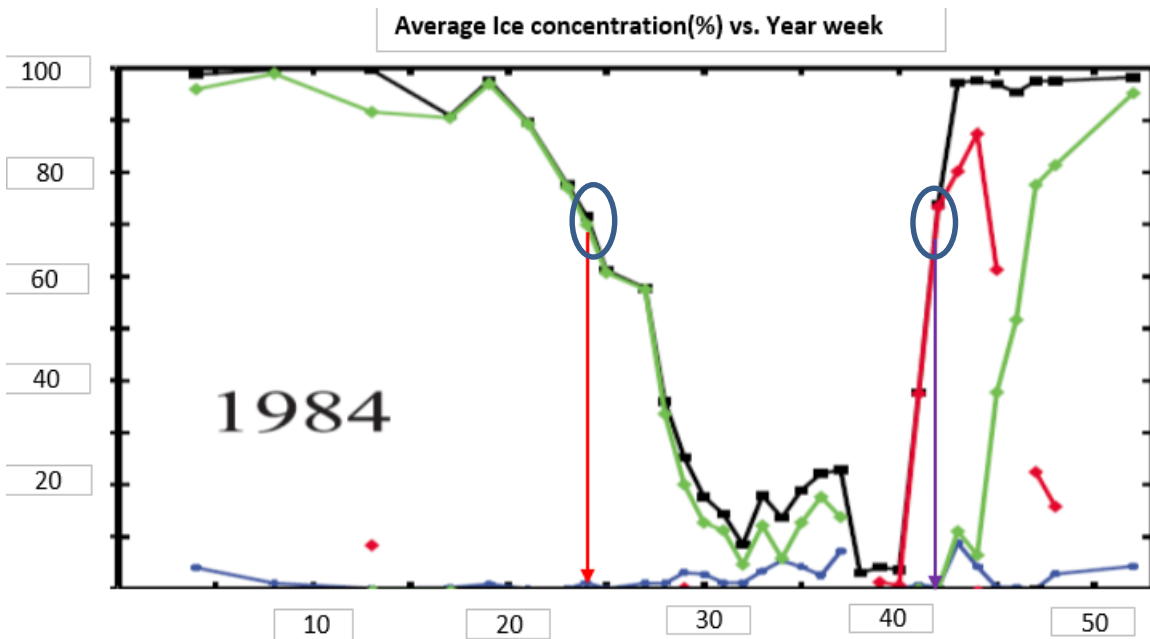


Figure 44: Sea ice concentration in the Beaufort Sea for selected years (Modified CIS data), showing total ice (in black), multi-year ice (in blue), first-year ice (in green), and new and young ice (in red)

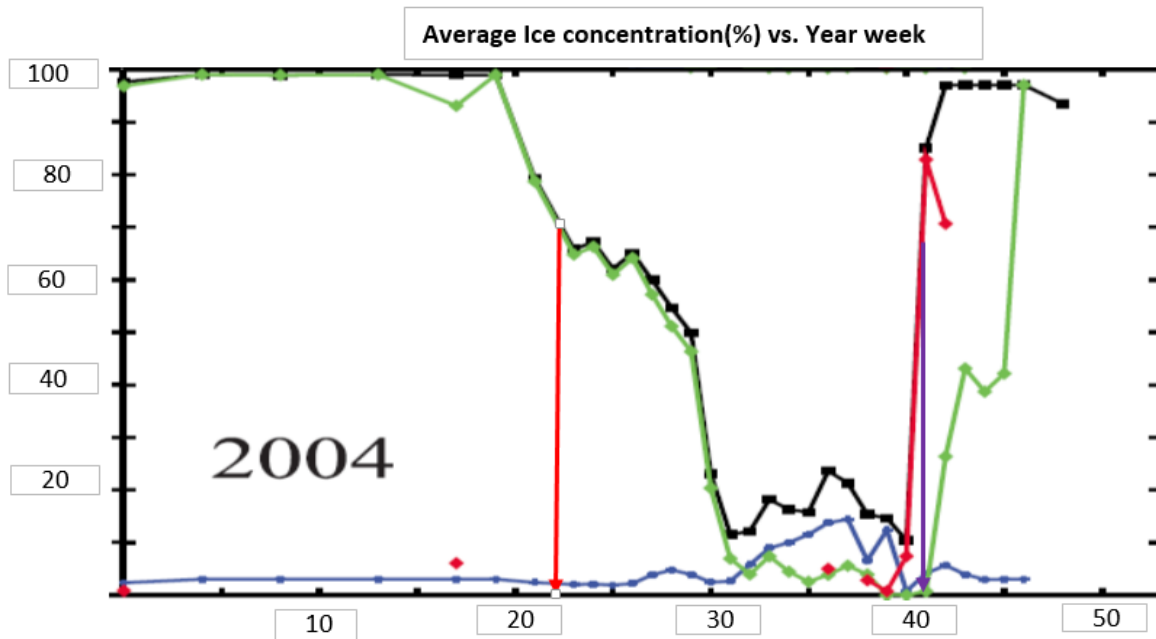


Figure 44: Sea ice concentration in the Beaufort Sea for selected years (Modified CIS data), showing total ice (in black), multi-year ice (in blue), first-year ice (in green), and new and young ice (in red)

Although, abnormal ice changes are seen in 25 years' worth of ice data, the ice concentration has a consistent pattern throughout the year. From the CIS ice data (1980 ~2004), we found that the ice-covered water (>80%) period lasted approximately 7 months (end of October to middle of May) and the open-water period occurred for 2 months (beginning of August to beginning of October) in the Beaufort Sea. In addition, the ice-melting period (9 weeks) is longer than the refreezing period (1 week) (Figure 45). The ice concentration trend is deeply correlated with temperature in the area. As discussed earlier, temperatures above zero happened between May and September.

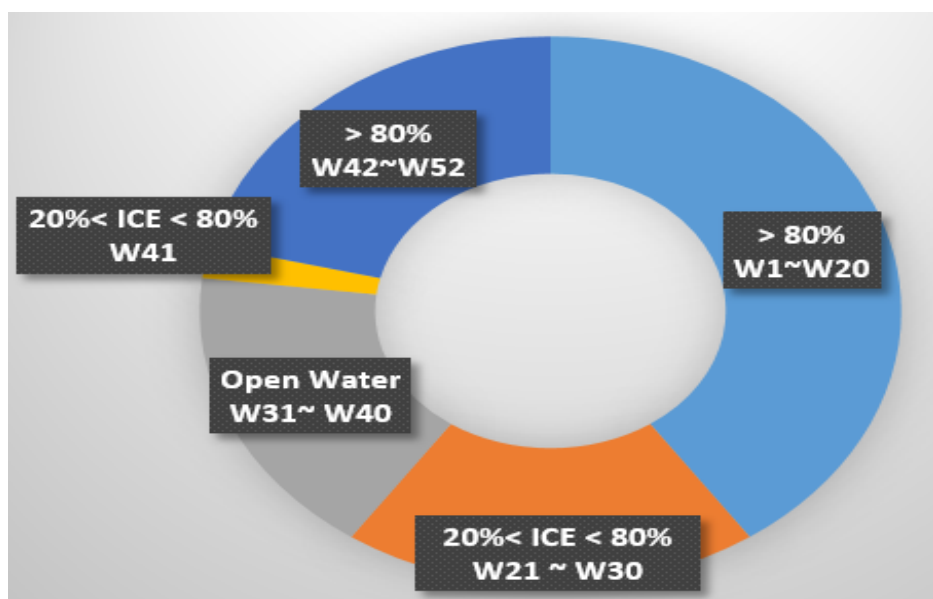


Figure 45. Typical ice concentrations and open-water periods, Beaufort Sea (Modified from CIS data)

5.3 OTEHR ENVIRONMENTAL FACTORS

To treat oil spills appropriately, environmental information is crucial. In particular, sea-depth information could be essential when an oil-removal plan using dispersants is considered. The Beaufort Sea has large shallower water areas (<100m); some areas could span a distance of more than 100 km from shorelines (Figure 46).

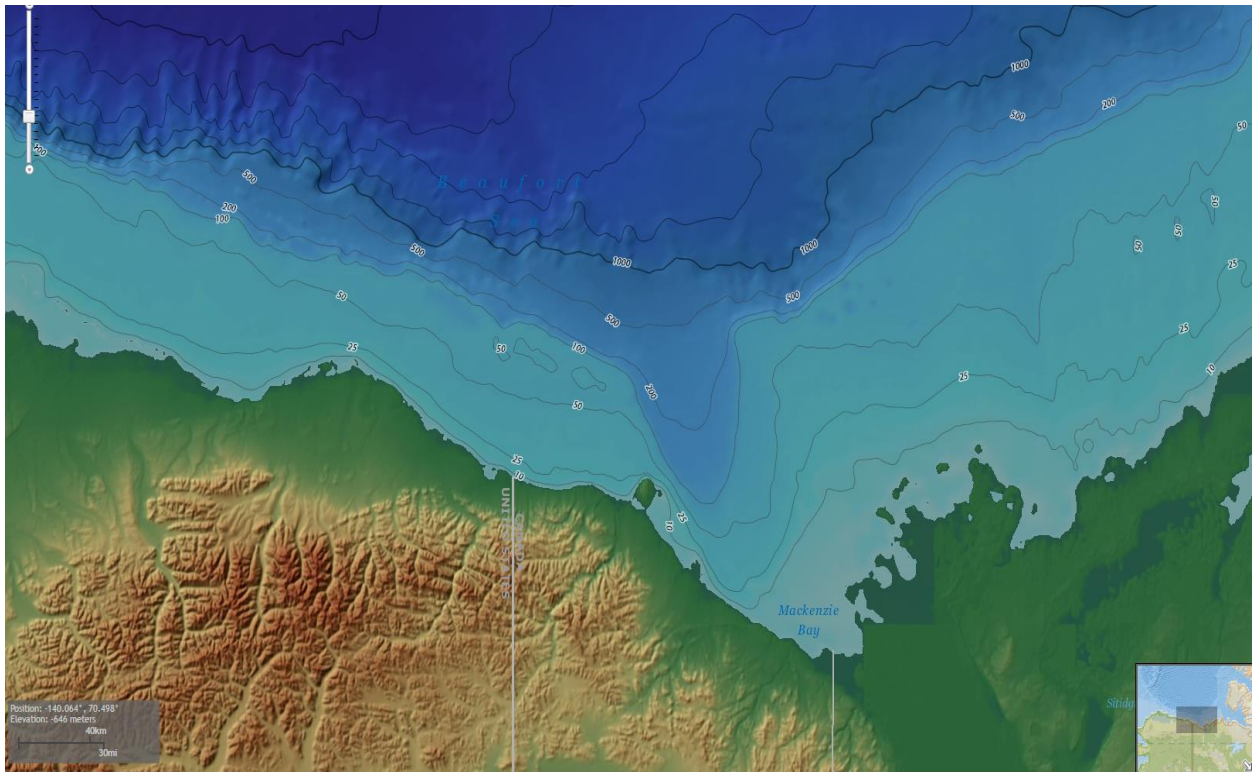


Figure 46. Bathymetric data, Beaufort Sea (NOAA, 2016)

These shallower areas are located in the land-fast zone. In the freezing season, the ice could be key to preventing oil spills from reaching shorelines. From the bathymetric data of the Beaufort Sea, it is clear that dispersant should be applied prudently in the event of oil spills during open-water season.

Due to the low salinity of sea ice, melting ice could decrease the salinity of the Beaufort Sea. Data (Figure 47) showed that shallower waters (<50 m) near shore areas tend to have lower salinity than deeper water. According to the Canadian Data Report (1988), salinity was lowered to 18 ppt in shallower water, whereas salinity of distant areas further from shore regions was higher (29-31 ppt).

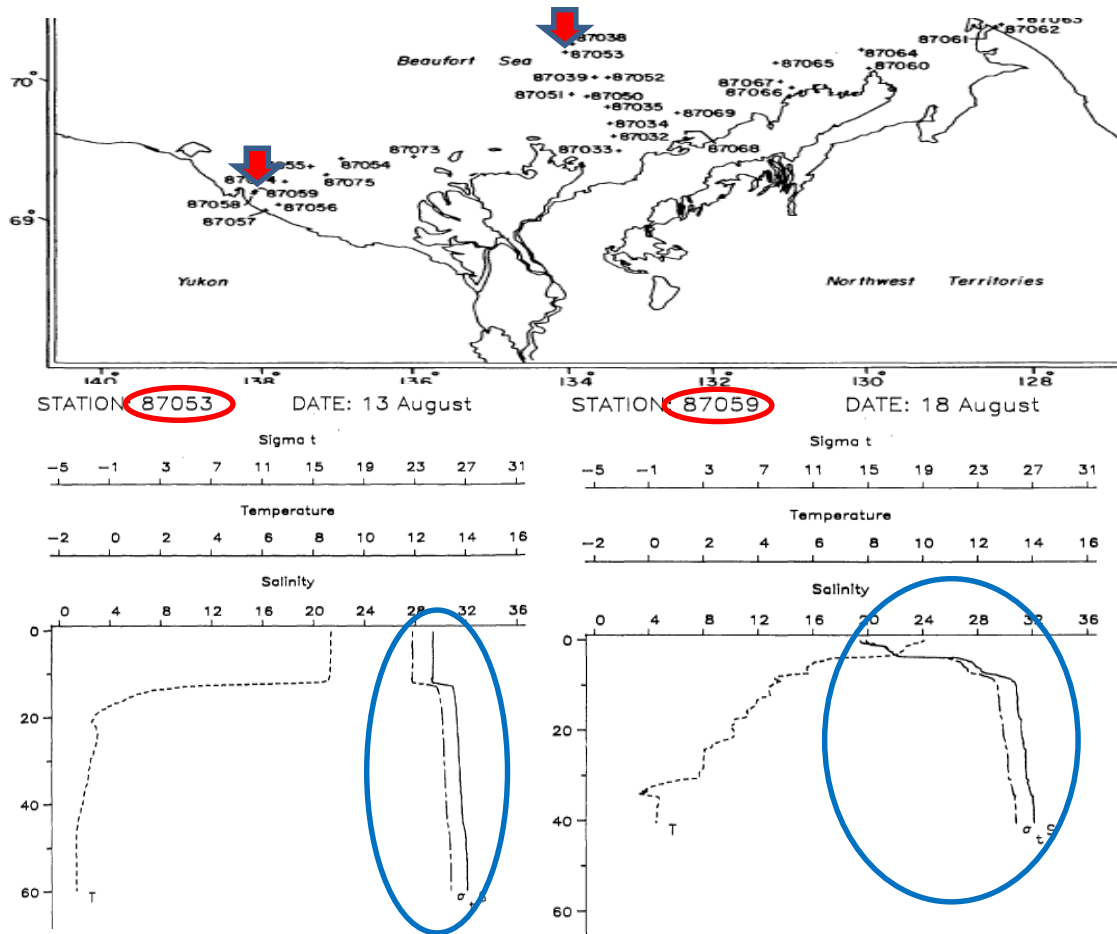


Figure 47. Salinity comparison in terms of the distance from shoreline (Hopky et al., 1988)

These results demonstrated that freshwater inflow and melting ice affected the low salinity in the shallow waters (Dickens and Owens, 2002). One possible conclusion is that the use of dispersants needs to be cautiously applied in shallow regions, not only for environmental impact but also to increase the efficient of the dispersant application.

5.4 OIL-SPILL RESPONSE IN OPEN-WATER SEASON

In the Beaufort Sea, the open-water (ice concentration < 20 %) season starts in August and lasts for 2 months. As temperature climbs, sea ice begins to melt in late May. It takes

approximately two months ($20\% < \text{ice concentration} < 80\%$) to be open water period in the Beaufort Sea.

Due to the extremely harsh environment in the Arctic, most hydrocarbon activities are conducted during open-water conditions (NPC, 2015). Hence, there is a higher possibility of oil spills in the region. When an oil spill occurs in the ocean during the open-water season, more consideration should be given to environmental factors affecting oil removal activity. Otherwise, open-water conditions in the Arctic are regarded as being the same as open waters in temperate regions (MMS, 2009).

In open-water conditions, spilled oil is likely to spread easily due to the external energy provided by sea waves. Therefore, enough oil thickness (< 0.1 inch) is hard to maintain to use in-situ burning. On the other hand, sea waves can be a window of opportunity for application of chemical dispersants. There are several factors to consider before dispersant application. Salinity ranges from 20 to 32 ppt which is an appropriate for using dispersants in the Beaufort Sea. Viscosity of spilled oil would have little impact on the use of dispersant due to the seasonal warm condition. In addition to dispersants application, mechanical oil recovery activities using skimmers could lead to higher oil removal efficiency in open waters.

5.5 OIL-SPILL RESPONSE IN ICE-COVERED WATER SEASON

The ice-covered-water season (ice concentration $> 70\%$) lasts for about 8 months (October to May) in the Beaufort Sea. During this period, oil-spill responses could be limited. However, environmental restrictions related to ice could be utilized as a way of effective oil spill response in this area. Ice concentration would be used as a natural barrier when oil spills into the sea. Natural containment by ice prevents oil slicks from spreading and control weathering effects by sea waves (Potter et al., 2012). Weather conditions associated with wind speed in this area are favorable to in situ burning (Figure 48).

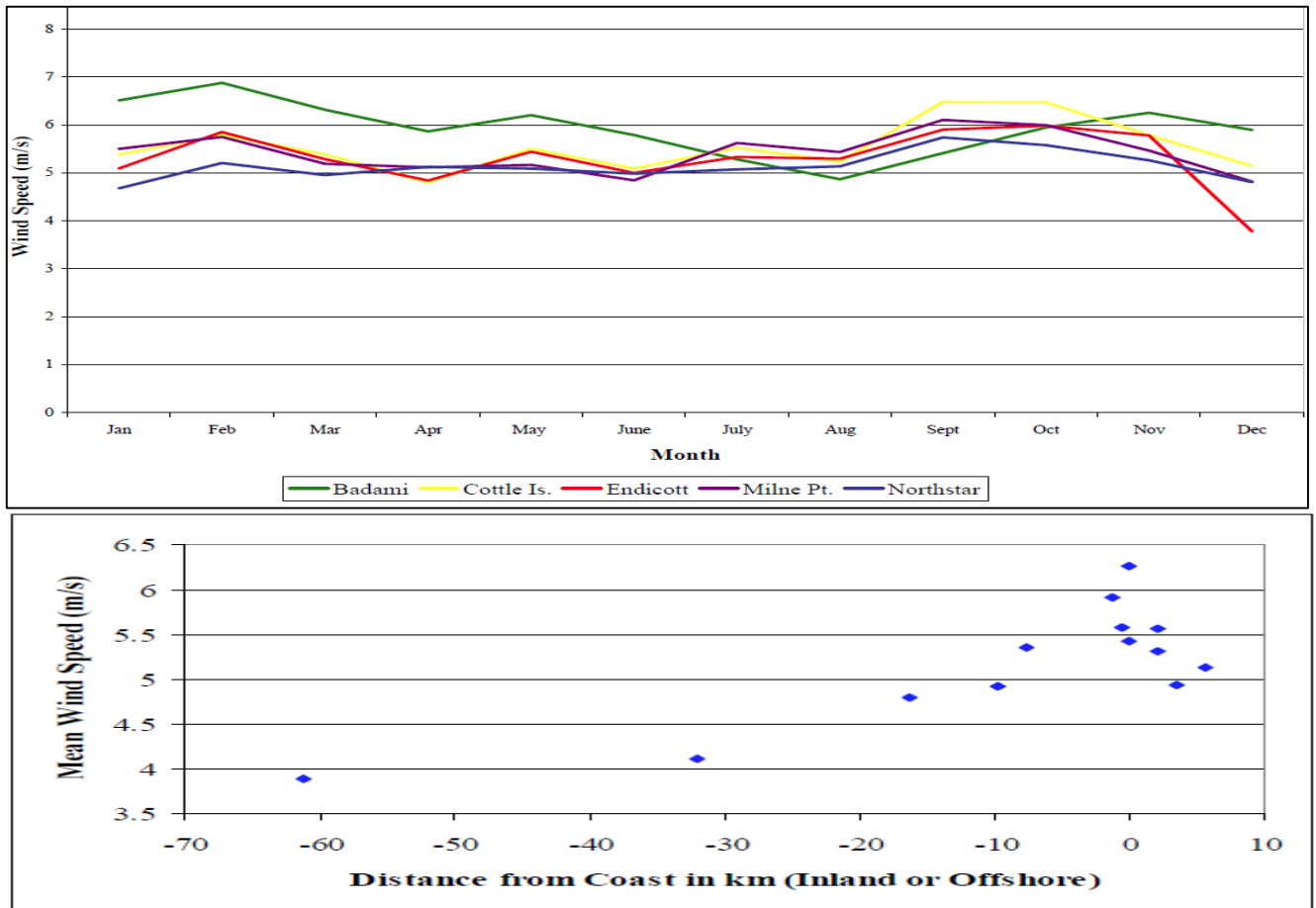


Figure 48. Average wind speed in the Beaufort Sea (Wilcox et al., 2007)

In ice-transitional periods (June to July, early October), prudent decision making is required to respond to oil spills effectively in terms of environmental factors. When temperature rises and falls, sea ice concentration varies as well. Historically, Beaufort Sea has relatively long ice melting periods (9 weeks), then refreezing periods (1 week) (Figure 45). During these periods, continuous inspection would be needed to deal with oil spills in the area. If ice concentration is below 70%, it is recommended to use chemical dispersants. Before the application of dispersants, several factors including temperature, salinity, and sea depth, should be taken into consideration.

6. CONCLUSION

Stakeholders including the oil and gas industry, have long sought to deal with oil spills effectively. The Deepwater Horizon disaster resulted in additional environmental concerns and pressure related to safe exploration and production activities in Arctic regions.

To deal with oil spills in Arctic waters, stakeholders are seeking a range of solutions, such as technical improvement in exploration and production equipment, in oil spill monitoring systems, and in oil-spill-response activities. This study examined oil-spill response in terms of ice concentration, climatic variables, and geologic conditions in the Arctic. This thesis also analyzed oil spill prevention and response to mitigate environmental and cost impacts.

This analysis of oil spill options in the Canadian Beaufort Sea shows that different methods of oil removal activities are required, mainly depending on ice concentration. This conclusion means that detailed information about the polluted area is essential for efficient clean up. Moreover, ice could be used as natural equipment for successful oil-spill-response. Therefore, the extreme environment of the Canadian Beaufort Sea might be the best place for oil cleanup.

Application of chemical dispersants in the area could also lead to successful oil-spill response. Ice-covered conditions in low temperatures could retard the process. Several published studies showed that environmental impact is limited to the marine ecosystem. However, it remains to be seen whether dispersant application potentially affects marine habitats. Due to the geologic characteristics (shallow waters up to 200km from shoreline) of the Canadian Beaufort Sea, dispersants application in shallower waters should be prudently considered. Therefore, additional monitoring and research on a long-term basis are required to ensure the safety of using chemical dispersants in the Arctic.

References

- Allen, A.A. (1990). Contained controlled burning of spilled oil during the Exxon Valdez oil spill, AMOP Technical Seminar. No. 13, pp. 305-313
- Allen, A.A. and R.J. Ferek. 1993. Advantages and disadvantages of burning spilled oil
- Anderson, A. (Sept. 1, 2010). Arctic oil and gas drilling ready to take o". NewScientist. www.newscientist.com/article/mg20727764.300-arctic-oil-and-gas-drilling-ready-to-take-o".html.
- API Spec.16A (June 2004) "Specification for Drill-Through Equipment", American Petroleum Institute, Washington, D.C, 3rd Edition.
- ASTM F2152 (2011). Standard Guide for In-situ Burning of Spilled Oil: Fire-Resistant Boom
- Belore, R., G.P. Canevari, J.R. Clark and Nedwed, T. (2008). New dispersant delivered as a gel.
- Belore, R., Trudel, K., M. VanHaverbeke and J. Mullin (2009). Updating the U.S. SMART dispersant efficacy monitoring protocol.
- Bureau of Minerals and Petroleum, Greenland. (2004). Weather, Sea and Ice Conditions Offshore Western Greenland.
- Bradford, J. H., D.F. Dickins, and P.J. Brandvik. (2010). Assessing the potential to detect oil spills in and under snow using airborne ground-penetrating radar. Geophysics 75(2): G1-G12.
- Brown, C. (2008). Oil detection in/under ice
- Buist, I.A. and Dickins, D.F. (1981). Oil and Gas under sea ice study: Vols. I&2
- Buist, I.A. (2004). In Situ Burning for Oil Spills in Ice-Covered Waters
- Buist, I., R. Belore, D. Dickins, A. Guarino, D. Hackenberg and Z. Wang. (2009). Empirical weathering properties of oil in ice and snow , Proceedings Arctic and Marine Oil spill Program (AMOP) Technical Seminar No.32, Vol. 1, pp. 67-107.
- Burns, B.M. (1973). The Climate of the Mackenzie Valley – Beaufort Sea. Volume 1. Climatological Studies Number 25. Environment Canada, 239 pp
- Byford, D.C., P.J. Green, and A. Lewis. (1983). Factors influencing the performance and selection of low temperature dispersants

- Campbell, T.G., Buist, I.A., S.L. Ross, B.K. Trudel, E. Taylor, P.A. Westphal, M.R. Myers, G.S. Ronzio, A.A. Allen, and A. B. Nordvik (1994). The science, technology and effects of controlled burning of oil spills at sea. Technical Report Series 94-013.
- Canadian Association of Petroleum Producers (2011). "Potential Oil and Gas Activities in the Beaufort," Presentation to National Energy Board, Arctic Offshore Drilling Review Sept. 12-16, 2011.
- Canadian Ice Service Archive Documentation Series (Sep. 2006). Regional Charts: History, Accuracy, and Caveats (http://ice.ec.gc.ca/IA_DOC/cisads_no_001_e.pdf).
- Cammaert, A. (1980). Oil and Gas under Laboratory ice laboratory Study. Beaufort Environmental Impact Statement RWC17.
- Chapman, H., K. Purnell, R. Law, M. Kirby. (2007). The use of dispersants to combat oil spills at sea: A review of practice and research needs in Europe. Marine Pollution Bulletin, 54 pp. 827-838
- Carr, E., Blasco, S, Bennett, R., Brent, T., Burton, M., Campbell, P., Covill, R., Dallimore, S. (2010) State of Knowledge : Beaufort Sea Seabed Geohazards Associated with Offshore Hydrocarbon Development
- Casey, K. (Jan. 2014). Greenland's New Frontier: Oil and Gas Licenses Issued Though Development Likely Years Off (published on the website of the Arctic Institute).
- Coe, T. and B. Gurr, (1999). Control of Oil Spills in Fast water Currents, A Technology Assessment.
- Clark., J., T. Coolbaugh, R. Belore, J. Mullin, R. Lessard, and A. Findlay (2009). Assessing the dispersibility of heavy and viscous oils
- Collett, T. (2008). Assessment of Gas Hydrate Resources on the North Slope, Alaska, USGS.
- Devon Canada (2004a). Comprehensive Study Report - Devon Beaufort Sea Exploration - Drilling Program
- DF Dickins Associates Ltd. SL Ross Environmental Research Ltd. and Envision Planning Solutions Inc. (2010). Beaufort Sea Oil Spills State of knowledge Review and Identification of Key Issues. Environmental Studies Research Funds Report No. 177. Calgary. pp. 126.
- Dickins, D.F. and I.A. Buist, (1981). Dome Petroleum's Study of Oil and Gas Under

- Sea Ice. Proceedings International Oil Spill Conference, American Petroleum Institute, Wash. D.C., pp 183-189.
- Dickins, D.F. and Owens (2002). Annual ice cycle at the mouth of the colville river and implications for oil transport
- Dickins, D.F. and J.H.S. Andersen (2009). Remote Sensing Technology Review and Screening. SINTEF Oil in Ice JIP, Report 22.
- Dickins, D.F. (2011). Behavior of Oil Spills in Ice and Implications for Arctic Spill Response, OTC 22126.
- Ebinger, C., Banks, J. and Schackmann, A. (2014). Offshore Oil and Gas Governance in the Arctic: A Leadership Role for the US. Brookings Institute: Washington D.C.
- Eik, K and Gudmestad, OT (2010). Iceberg management and impact on design of offshore structures, Cold Regions Science and Technology 63. pp 15–28.
- Exxon Neftegas Limited (Sep. 2014). Sakhalin-1 Project Breaks Own Record for Drilling World's Longest Extended-Reachwell. (http://www.sakhalin-1.com/Sakhalin/Russia-English/Upstream/media_news_events_Z44.aspx).
- Farmwald, J.W. and W.G. Nelson (1982). Dispersion characteristics and flammability of oil under low ambient temperature conditions.
- Fingas, M.F., D.A. Kyle, N. Laroche, B. Fieldhouse, G. Sergy and G. Stoodley (1995). The effectiveness of oil spill treating agents.
- Fingas, M.F. and C.E. Brown (2011). Oil spill remote sensing: A review. pp. 111-158 in Oil Spill Science and Technology, edited by M. Fingas. Gulf Professional Publishing, Burlington, MA.
- Fodrie F.J. and K.L. Heck, Jr. (2011). Response of coastal fishes to the Gulf of Mexico oil disaster.
- Gautier, D. (2008). Circum-Arctic Resource Appraisal: Estimates of Undiscovered Oil and Gas North of the Arctic Circle, USGS.
- Gautier, D. (2011). Chapter 9: Oil and Gas Resource Potential North of the Arctic Circle (originally published by The Geological Society of London), USGS.
- Government of Greenland (July 2014). Mineral License and Safety Authority.
- Guénette, C.C. and P. Sveum. (1995). Emulsion breaking igniters: recent developments in oil spill igniter concepts, AMOP) Technical Seminar. No. 18,

- Guénette, C.C. and J. Thornborough. (1997). An assessment of two offshore igniter concepts. AMOP Technical seminar: No. 20b:795-808.
- Hamilton, Jed and Neal Prescott (Sep. 2014). Arctic Subsea Pipelines and Subsea Production Facilities.
- Hansen, Kurt A (2002). Evaluation of New Approaches to the Containment and Recovery of Oil in Fast Water.
- Hansen, K. (2013). Ice and Metocean conditions off the Northeast Coast of Greenland, Danish Meteorological Institute, Center for Ocean and Ice.
- Hayes, David, Joel P. Clement, John L. Bengtson, Brendan P. Kelly (Mar. 2013). Managing for the Future in a Rapidly Changing Arctic.
- Henderson, James and Julia Loe (Nov. 2014). The Prospects and Challenges for Arctic Oil Development.
- Hopky, G.E., D.B. Chipczak and M.J. Lawrence (Mar. 1988). Seasonal Salinity, Temperature and Density data for the Canadian Beaufort Sea Shelf
- IHS (Sep. 2014). International E&P Database (online).
- ION (Aug. 2014). Exploration data acquisition in the arctic offshore.
- ITOPF (2014). Use of skimmers in oil pollution response, (<http://www.itopf.com/knowledge-resources/documents-guides/document/tip-5-use-of-skimmers-in-oil-pollution-response/>).
- Iyerusalimskiy, A., Gregory Dean Davis, Alexander G. Suvorov, Valery V. Kravchenko, Sergey P. Petrov (2007). Arctic Crude Oil Transportation System Development.
- Johannessen, B.O. and Vefsnmo, S. (1994). Experimental Oil Spill in the Barents Sea - Drift and Spread of Oil in Broken Ice.
- Johnson, D. W., C. G. Kilsby, D. S. McKenna, R. W. Saunders, G. J. Jenkins, F. B. Smith, and J. S. Foot (1991). Airborne observations of the physical and chemical characteristics of the Kuwait oil smoke plume. *Nature*, v353, pp617-621.
- Kokkinis, T, Brinkmann, CR, Ding, J, and Fenz, DM (2010). Arctic Deepwater

Development Drilling Design Considerations, Paper Icetech10-115-RF, Proceedings, Icetech 2010 Conference, Anchorage, Alaska.

Kovacs, A., and Mellor, M. (1974). Sea Ice Morphology and Ice as a Geologic Agent in the Southern Beaufort Sea

Leifer, I., W.J. Lehr, D. Simecek-Beatty, E. Bradley, R. Clark, P. Dennison, H. Yongxiang, S. Matheson, C.E. Jones, B. Holg, M. Reif, D. A. Roberts, J. Sveikovsky, G. Swayze, and JI. ozencraft (2012). State of the art satellite and airborne marine oil spill remote sensing: Application to the BP Deepwater Horizon oil spill. Elsevier. Remote Sensing of Environment 124: 185-209.

Lewis, A. and P.S. Daling (2007). Oil in ice: A review of studies of oil spill dispersant effectiveness in Arctic conditions.

Lunden, L. P., Lindgren, P., Loe, J. and Fjærtøft, D. (2011). Commerciality of Arctic Offshore Gas: A Comparative Study of the Snøhvit and Burger Fields, report prepared for the Geopolitics in the High North Project (http://geopoliticsnorth.org/images/stories/attachments/Econ%202_2011.pdf).

Lunden, L.P. and Fjaertoft, D. (2012). Twenty years of development and still no oil: Pirazlomnoye – Russia’s troublesome first Arctic offshore oil development p.2.

Madrid, Mauricio and Antony Matson (2014). How Offshore Capping Stacks Work.

Mancini C.V., S. Dowse and Jean Chevallier (1978). Caisson Retained Island for Canadian Beaufort Sea-Geotechnical Design and Construction Considerations.

Masterson, D.M., J.C. Bruce, R. Sisodiya, and W. Maddock (1991). Beaufort Sea Exploration: Past and Future (OTC 6530), presented at 23rd Annual OTC, Annual OTC, Houston, Texas, May 6-9, 1991.

Minerals management service, U.S. department of the interior (2009). Arctic oil spill response research and development program.

Ministry of Petroleum and Energy (2014). Facts 2014: The Norwegian Petroleum Sector. (http://www.regjeringen.no/upload/OED/pdf%20filer/Faktaheftet/Fakta2014OG/Facts_2014_net.pdf).

Moyer, Mark C, Scott B. Lewis, Mike T. Cotton, L. Miles Peroyea (2012). Challenges associated with drilling a deepwater, subsalt exploration well in the Gulf of Mexico : Hadrian prospect.

National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling,

- Washington, D.C. (Jan. 2011). Deep Water: The Gulf Oil Disaster and the Future of Offshore Drilling.
- National Oceanic and Atmospheric Administration (2007). Open water oil identification job aid for aerial observation; New Standardized Oil Slick Appearance and Structure Nomenclature and Code. (<http://www.response.restoration.noaa.gov/>).
- National Petroleum Council (2011). Prudent Development: Realizing the Potential of North America's Abundant Natural Gas and Oil Resources.
- National Petroleum Council (2015). Arctic Potential.
- NPD (2014). <http://npd.no/Nyheter/Resultat-av-leteboring/2014/73251-1/>.
- National Research Council (2005). Oil Spill Dispersants: Efficacy and Effects.
- Nedwed, T., G.P. Canevari, J.R. Clark and R. Belore. (2008). New dispersant delivered as a gel.
- Nedwed, T., Srnka, L., and Thomann, H. (2008). Remote Detection of Oil Spilled under Ice and Sno using Nuclear Magnetic Resonance. Proceedings of the 31st Arctic and Marine Oilspill Program (AMOP) Technical Seminar. Calgary, AB Canada, Environment Canada:693-702.
- Noble, P (Aug. 2014). Offtake and Tankering.
- Nunaoil Annual Report (2013), p. 6
- Palmer, A.C., Andrew Palmer & Assocs.; C.P. Ellinas, Advanced Mechanics & engineering; OTC 6335D.M. Richards, L10yds Register; and J. Guijt, AIS Norske Shell (1990). Design of Submarine Pipelines Against Upheaval Buckling.
- Palmer, A.C. (2000). Are we ready to construct submarine pipelines in the Arctic? Proceedings, 32nd Annual Offshore Technology Conference, OTC 2000, Houston, TX, USA, 3, Paper OTC12183, 737-744.
- Petroleum Economist (Feb. 2014). North America's Arctic drive idles.
- Petroleum Research Newfoundland & Labrador (2014). Joint Industry Program: Development of Improved Ice Management Capabilities for Operations in Arctic and Harsh environments. (<http://www.petroleumresearch.ca>).
- Postler, D.P. (1997). Pressure Integrity test interpretation. SPE/IADC 37589.

- Potter, S., Ian Buist and Ken Trudel, David Dickins, Ed Owens (Feb. 2012). Spill response in the Arctic Offshore.
- Prince, R. and J. Butler (2014). A protocol for assessing the effectiveness of oil spill dispersants in stimulating the biodegradation of oil.
- Rice, S., T. Dudley, C. Schneider, R. Pierce, B. Horn, S. Cameron, R. Bloor, and Z. Zhou (May 2013). Arctic seismic acquisition and processing. The Leading Edge.
- Samad, T and A.M. Annaswamy (2011). Dynamic Positioning System for Marine Vessels. (<http://www.ieeecss.org/sites/ieeecss.org/files/documents/IOCT-Part2-18MarineVessels-LR.pdf>).
- Schenk, C.J. (2012). An Estimate of Undiscovered Conventional Oil and Gas Resources of the World, USGS.
- SINTEF (2010). www.sintef.no/Projectweb/JIP-Oil-In-Ice/Publications/.
- SL Ross Environmental Research (SL Ross). (2010). Literature review of chemical oil spill dispersants and herders in fresh and brackish waters.
- Sørstrøm, S.E., P.J. Brandvik, I. Buist, P. Daling, D. Dickins, L-G. Faksness, S. Potter, J.F. Rasmussen and I. Singaas (2010). Joint industry program on oil spill contingency for Arctic and ice-covered waters: Summary Report. SINTEF report A14181.
- Spedding, L.G. (1978). Statistics of Beaufort Sea Summer Ice Cover for Ice/Structure Interaction Collision Assessment.
- Spring, W., T. Nedwed and R. Belore (2006). Icebreaker enhanced chemical dispersion of oil spills.
- Sveum, P. and C. Bech (1991). Burning of oil in snow: experiments and implementation in a Norsk Hydro drilling contingency plan. AMOP Technical Seminar. No. 14, pp. 399-410.
- Thodi, Premkumar, Mike Paulin, Duane DeGeer, and Glenn Lanan (2012). INTECSEA Canada, Offshore pipeline leak detection for Arctic applications.
- Timco, G.W. and R. Frederking (2013). Overview of Historical Canadian Beaufort Sea Information.
- U.S. Coast Guard Research and Development Center (2011). Evaluation of four oil spill recovery devices in fast water conditions at OHMSETT.

Wilcox, J.R. (2007). Beaufort Sea Meteorological monitoring and data synthesis project.

Wilson Center (2014). Opportunities and Challenges for Arctic Oil and Gas Development, Eurasia Group report, Washington, D.C., 2014, p12.

Wood Mackenzie (2014). Shtokman LNG Asset Report, Houston.